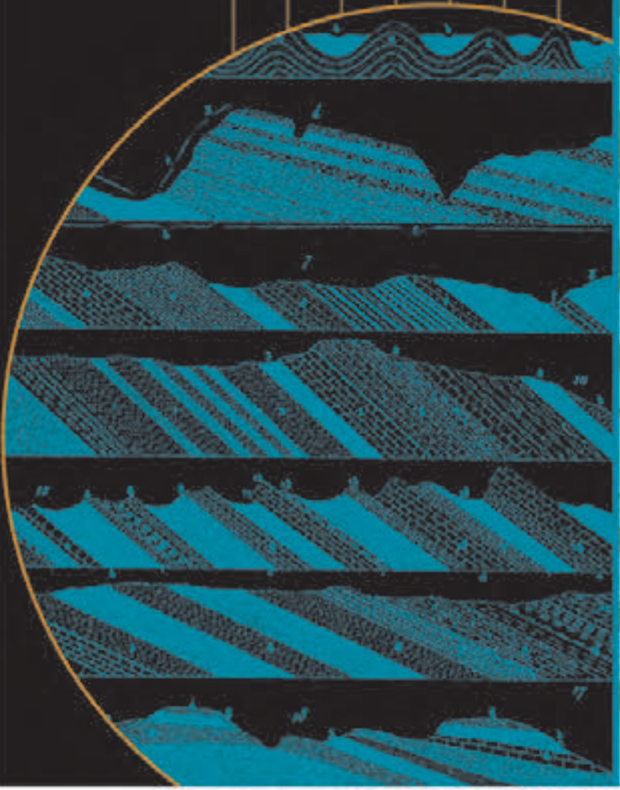
WORLD *of*
EARTH SCIENCE



WORLD *of* EARTH SCIENCE

WORLD *of* EARTH SCIENCE

K. Lee Lerner and Brenda Wilmoth Lerner, *Editors*

Volume 1

A-L

GALE GROUP
THOMSON LEARNING™

Detroit • New York • San Diego • San Francisco
Boston • New Haven, Conn. • Waterville, Maine
London • Munich

THOMSON
™
GALE

World of Earth Science

K. Lee Lerner and Brenda Wilmoth Lerner

Project Editor
Ryan L. Thomason

Editorial
Deirdre S. Blanchfield, Madeline Harris, Kate Kretschmann, Michael D. Lesniak, Kimberley A. McGrath, Brigham Narins, Mark Springer

Permissions
Shalice Shah-Caldwell

Imaging and Multimedia
Robert Duncan, Leitha Etheridge-Sims, Lezlie Light, Kelly A. Quin, Barbara J. Yarrow

Product Design
Michael Logusz, Tracey Rowens

Manufacturing
Wendy Blurton, Evi Seoud

© 2003 by Gale. Gale is an imprint of The Gale Group, Inc., a division of Thomson Learning, Inc.

Gale and Design™ and Thomson Learning™ are trademarks used herein under license.

For more information contact
The Gale Group, Inc.
27500 Drake Rd.
Farmington Hills, MI 48331-3535
Or you can visit our Internet site at
http://www.gale.com

ALL RIGHTS RESERVED
No part of this work covered by the copyright hereon may be reproduced or used in any form or by any means—graphic, electronic, or mechanical, including photocopying, recording, taping, Web distribution, or information storage retrieval systems—without the written permission of the publisher.

For permission to use material from this product, submit your request via Web at http://www.gale-edit.com/permissions, or you may download our Permissions Request form and submit your request by fax or mail to:

The Gale Group, Inc.,
Permissions Department,
27500 Drake Road,
Farmington Hills, MI, 48331-3535,
Permissions hotline:
248-699-8074 or 800-877-4253, ext. 8006,
Fax: 248-699-8074 or 800-762-4058.

While every effort has been made to ensure the reliability of the information presented in this publication, The Gale Group, Inc. does not guarantee the accuracy of the data contained herein. The Gale Group, Inc. accepts no payment for listing; and inclusion in the publication of any organization, agency, institution, publication, service, or individual does not imply endorsement of the editors and publisher. Errors brought to the attention of the publisher and verified to the satisfaction of the publisher will be corrected in future editions.

ISBN 0-7876-7739-6 (set)
0-7876-7740-X (vol. 1)
0-7876-7741-8 (vol. 2)

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA

World of earth science / K. Lee Lerner and Brenda Wilmoth Lerner, editors.
p. cm.
Includes bibliographical references and index.
ISBN 0-7876-7739-6 (set)—ISBN 0-7876-7740-X (v. 1)—ISBN 0-7876-7741-8 (v. 2)
1. Earth sciences—Encyclopedias. I. Lerner, K. Lee. II. Lerner, Brenda Wilmoth.
QE5 .W59 2003
550′.3—dc21 2002012069

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

CONTENTS

C

D

E

F

G

H

I

J

K

L

P

Q

R

S

T

U

V

INTRODUCTION

As of June 2002, astronomers had discovered more than 100 other planets orbiting distant suns. With advances in technology, that number will surely increase during the opening decades of the twenty-first century. Although our explorations of the Cosmos hold great promise of future discoveries, among all of the known worlds, Earth remains unique. Thus far it is the only known planet with blue skies, warm seas, and life. Earth is our most tangible and insightful laboratory, and the study of Earth science offers us precious opportunities to discover many of the most fundamental laws of the Universe.

Although Earth is billions of years old, geology—literally meaning the study of Earth—is a relatively new science, having grown from seeds of natural science and natural history planted during the Enlightenment era of the eighteenth and nineteenth centuries. In 1807, the founding of the Geological Society of London, the first learned society devoted to geology, marked an important turning point for the science (some say its nascence). In the beginning, geologic studies were mainly confined to the study of minerals (mineralogy), strata (stratigraphy), and fossils (paleontology), and hotly debated issues of the day included how well new geologic findings fit into religious models of creation. In less than two centuries, geology has matured to embrace the most fundamental theories of physics and chemistry—and broadened in scope to include the diverse array of subdisciplines that comprise modern Earth science.

Modern geology includes studies in seismology (earthquake studies), volcanology, energy resources exploration and development, tectonics (structural and mountain building studies), hydrology and hydrogeology (water-resources studies), geologic mapping, economic geology (e.g., mining), paleontology (ancient life studies), soil science, historical geology and stratigraphy, geological archaeology, glaciology, modern and ancient climate and ocean studies, atmospheric sciences, planetary geology, engineering geology, and many other subfields. Although some scholars have traditionally attempted to compartmentalize geological sciences into subdisciplines, the modern trend is to incorporate a holistic view of broader Earth science issues. The incorporation of once-diverse fields adds strength and additional relevance to geoscience studies.

World of Earth Science is a collection of 650 entries on topics covering a diversity of geoscience related interests—from biographies of the pioneers of Earth science to explanations of the latest developments and advances in research. Despite the complexities of terminology and advanced knowledge of mathematics needed to fully explore some of the topics (e.g., seismology data interpretation), every effort has been made to set forth entries in everyday language and to provide accurate and generous explanations of the most important terms. The editors intend *World of Earth Science* for a wide range of readers. Accordingly, *World of Earth Science* articles are designed to instruct, challenge, and excite less experienced students, while providing a solid foundation and reference for more advanced students.

World of Earth Science has attempted to incorporate references and basic explanations of the latest findings and applications. Although certainly not a substitute for in-depth study of important topics, we hope to provide students and readers with the basic information and insights that will enable a greater understanding of the news and stimulate critical thinking regarding current events (e.g., the ongoing controversy over the storage of radioactive waste) that are relevant to the geosciences.

The broader and intellectually diverse concept of Earth science allows scientists to utilize concepts, techniques, and modes of thought developed for one area of the science, in the quest to solve problems in other areas. Further, many geological problems are interrelated and a full exploration of a particular phenomenon or problem demands overlap between subdisciplines. For this reason, many curricula in geological sciences at universities stress a broad geologic education to prepare graduates for the working world, where they may be called upon to solve many different sorts of problems.

World of Earth Science is devoted to capturing that sense of intellectual diversity. True to the modern concept of Earth science, we have deliberately attempted to include some of the most essential concepts to understanding Earth as a dynamic body traveling through space and time.

Although no encyclopedic guide to concepts, theories, discoveries, pioneers, issues and ethics related to Earth science could hope to do justice to any one of those disciplines in two volumes, we have attempted to put together a coherent collection of topics that will serve not only to ground students in the essential concepts, but also to spur interest in the many diverse areas of this increasing critical set of studies.

In addition to topics related to traditional geology and meteorology, we have attempted to include essential concepts in physics, chemistry, and astronomy. We have also attempted to include topical articles on the latest global positioning (GPS), measurement technologies, ethical, legal, and social issues and topics of interest to a wide audience. Lastly, we have attempted to integrate and relate topics to the intercomplexities of economics and geopolitical issues.

Such a multifaceted and "real world" approach to the geosciences is increasingly in demand. In the recent past, geologic employment was dominated by the petroleum industry and related geologic service companies. In the modern world, this is no longer so. Mining and other economic geology occupations (e.g., prospecting and exploration), in former days plentiful, have also fallen away as major employers. Environmental geology, engineering geology, and ground water related jobs are more common employment opportunities today. As these fields are modern growth areas with vast potential, this trend will likely hold true well into the future. Many modern laws and regulations require that licensed, professional geologists supervise all or part of key tasks in certain areas of engineering geologic work and environmental work. It is common for professional geologists and professional engineers to work together on such projects, including construction site preparation, waste disposal, ground-water development, engineering planning, and highway construction. Many federal, state, and local agencies employ geologists, and there are geologists as researchers and teachers in most academic institutions of higher education.

Appropriate to the diversity of Earth science, we attempted to give special attention to the contributions by women and scientists of diverse ethnic and cultural backgrounds. In addition, we have included special articles written by respected experts that are specifically intended to make *World of Earth Science* more relevant to those with a general interest in the historical and/or geopolitical topics aspects of Earth science.

The demands of a dynamic science and the urgency of many questions related to topics such as pollution, global warming, and ozone depletion place heightened demands on both general and professional students of geosciences to increasingly broaden the scope and application of their knowledge.

For example, geological investigations of ancient and modern disasters and potential disasters are important—and often contentious—topics of research and debate among geologists today. Among the focus areas for these studies are earthquake seismicity studies. While much work continues in well-known problem areas like southern California, Mexico City, and Japan, less well-known, but potentially equally dangerous earthquake zones like the one centered near New Madrid, Missouri (not far from Memphis, Tennessee and St. Louis, Missouri) now receive significnt research attention. Geologists cannot prevent earthquakes, but studies can help predict earthquake events and help in planning the design of earthquake-survivable structures. Another focus of study is upon Earth's volcanoes and how people may learn to live and work around them. Some volcanoes are so dangerous that no one should live near them, but others are more predictable. Earthquake prediction and planning for eruptions is going on today by looking at the geologic record of past eruptions and by modern volcano monitoring using thermal imaging and tilt or motion-measuring devices. Other foci of disaster prevention research include river-flood studies, studies of slope stability (prevention of mass movement landslides), seismic sea-wave (tsunami) studies, and studies of possible asteroid or comet impacts.

Aside from geologic studies of disaster, there is a side of geology centered upon providing for human day-to-day needs. Hydrology is an interdisciplinary field within geology that studies the relationship of water, the earth, and living things. A related area, hydrogeology, the study of ground water, has undergone a revolution recently in the use of computer modeling to help understand flow paths and characteristics. These studies of water flow on the surface and in the subsurface connect with other subdisciplines of geology, such as geomorphology (the study of landforms, many of which are formed by water flow), river hydrology, limnology (study of lakes), cave and sinkhole (karst) geology, geothermal energy, etc. Geologic studies related to human and animal health (i.e., medical geology) are becoming very common today. For example, much work is currently devoted to tracing sources of toxic elements like arsenic, radon, and mercury in rock, soil, air, water, and groundwater in many countries, including the United States. There has been a major effort on the part of medical geologists to track down dangerous mineral species of asbestos (not all asbestos is harmful) and determine how best to isolate or remove the material. Atmospheric scientists have been at work for some years on the issue of air-born pathogens, which ride across oceans and continents born on fine soil particles lifted by winds.

Geologists are also focused on study of the past. Today, paleobotany and palynology (study of fossil spores and pollen) complement traditional areas of invertebrate and vertebrate paleontogy. Recent discoveries such as small, feathered dinosaurs and snakes with short legs are helping fill in the ever-shrinking gaps within the fossil record of evolution of life on Earth. Paleontologic studies of extinction, combined with evidence of extraterrestrial bombardment, suggest that mass death and extinction of species on Earth at times in the past has come to us from the sky. In a slightly related area, geoarchaeology, the geologic context of archaeological remains and the geologic nature of archaeological artifacts remains key to interpreting details about the pre-historic human past. Careful study of drilling records of polar ice sheets, deep-sea sediments, and deep lake sediments has recently revealed that many factors, including subtle variations in some of Earth's orbital parameters (tilt, wobble, and shape of orbit around the Sun), has had a profound, cyclical effect upon Earth's climate in the past (and is continuing today). Paleontologic studies, combined with geologic investigations on temperature sensitive ratios of certain isotopes (e.g. O^{16}/O^{18}), have helped unlock mysteries of climate change on Earth (i.e., the greenhouse to icehouse vacillation through time).

Earth science studies are, for the first time, strongly focused on extraterrestrial objects as well. Voyages of modern exploratory spacecraft missions to the inner and outer planets have sent back a wealth of images and data from the eight major planets and many of their satellites. This has allowed a new field, planetary geology, to take root. The planetary geologist is engaged in photo-geologic interpretation of the origin of surface features and their chronology. Planetary geologic studies have revealed some important comparisons and contrasts with Earth. We know, for example, some events that affected our entire solar system, while the effects of other events were unique to certain planets and satellites. In addition, planetary geologists have found that impact-crater density is important for determining relative age on many planets and satellites. As a result, Earth is no longer the only planet with a knowable geologic time scale.

The geosciences have undergone recent revolutions in thought that have profoundly influenced and advanced human understanding of Earth. Akin to the fundamental and seminal concepts of cosmology and nucleosynthesis, beginning during the 1960s and continuing today, the concept of plate tectonics has revolutionized geologic thought and interpretation. Plate tectonics, the concept that the rigid outer part of Earth's crust is subdivided into plates, which move about on the surface (and have moved about on the surface for much of geologic time) has some profound implications for all of geology. This concept helps explain former mysteries about the distribution of volcanoes, earthquakes, and mountain chains. Plate tectonics also helps us understand the distribution of rocks and sediments on the sea floor, and the disparity in ages between continents and ocean floors. Plate motion, which has been documented through geologic time, helps paleontologists explain the distribution of many fossil species and characteristics of their ancient climates. Plate tectonic discoveries have caused a rewriting of historical geology textbooks in recent years.

Although other volumes are chartered to specifically explore ecology related issues, the topics included in *World of Earth Science* were selected to provide a solid geophysical foundation for ecological or biodiversity studies. We have specifically included a few revolutionary and controversial concepts, first written about in a comprehensive way during the 1970s, such as the Gaia hypothesis. Simply put, Gaia is the notion that all Earth systems are interrelated and interconnected so that a change in one system changes others. It also holds the view that Earth functions like a living thing. Gaia, which is really a common-sense philosophic approach to holistic Earth science, is at the heart of the modern environmental movement, of which geology plays a key part.

Because Earth is our only home, geoscience studies relating meteor impacts and mass extinction offer a profound insight into delicate balance and the tenuousness of life. As Carl Sagan wrote in *Pale Blue Dot: A Vision of the Human Future in Space*, "The Earth is a very small stage in a vast cosmic arena." For humans to play wisely upon that stage, to secure a future for the children who shall inherit Earth, we owe it to ourselves to become players of many parts, so that our repertoire of scientific knowledge enables us to use reason and intellect in our civic debates, and to understand the complex harmonies of Earth.

K. Lee Lerner & Brenda Wilmoth Lerner, editors
London
May, 2002

How to Use the Book

The articles in the book are meant to be understandable by anyone with a curiosity and willingness to explore topics in Earth science. Cross-references to related articles, definitions, and biographies in this collection are indicated by **bold-faced type**, and these cross-references will help explain, expand, and enrich the individual entries.

This first edition of *World of Earth Science* has been designed with ready reference in mind:

- **Entries are arranged alphabetically**, rather than by chronology or scientific field.
- **Bold-faced terms** direct reader to related entries.
- **"See also" references** at the end of entries alert the reader to related entries not specifically mentioned in the body of the text.
- A **Sources Consulted** section lists the most worthwhile print material and web sites we encountered in the compilation of this volume. It is there for the inspired reader who wants more information on the people and discoveries covered in this volume.
- The **Historical Chronology** includes many of the significant events in the advancement of the diverse disciplines of Earth science. The most current entries date from just days before *World of Earth Science* went to press.
- A **comprehensive General Index** guides the reader to topics and persons mentioned in the book. Bolded page references refer the reader to the term's full entry.

A detailed understanding of physics and chemistry is neither assumed nor required for *World of Earth Science*. In preparing this text, the editors have attempted to minimize the incorporation of mathematical formulas and to relate physics concepts in non-mathematical language. Accordingly, students and other readers should not be intimidated or deterred by chemical nomenclature. Where necessary, sufficient information regarding atomic or chemical structure is provided. If desired, more information can easily be obtained from any basic physics or chemistry textbook.

For those readers interested in more information regarding physics related topics, the editors recommend Gale's *World of Physics* as an accompanying reference. For those readers interested in a more comprehensive treatment of chemistry, the editors recommend Gale's *World of Chemistry*.

In an attempt to be responsive to advisor's requests and to conform to standard usage within the geoscience community, the editors elected to make an exception to previously used style guidelines regarding geologic time. We specifically adopted the convention to capitalize applicable eons, eras, periods and epochs. For example, Cenozoic Era, Tertiary Period, and Paleocene Epoch are intentionally capitalized.

Advisory Board

In compiling this edition, we have been fortunate in being able to rely upon the expertise and contributions of the following scholars who served as academic and contributing advisors for *World of Earth Science*, and to them we would like to express our sincere appreciation for their efforts to ensure that *World of Earth Science* contains the most accurate and timely information possible:

Cynthia V. Burek, Ph.D.
Environment Research Group, Biology Department
Chester College, England, U.K.

Nicholas Dittert, Ph.D.
Institut Universitaire Européen de la Mer
University of Western Brittany, France

William J. Engle. P.E.
Exxon-Mobil Oil Corporation (Rt.)
New Orleans, Louisiana

G. Thomas Farmer, Ph.D., R.G.
Earth & Environmental Sciences Division,
Los Alamos National Laboratory
Los Alamos, New Mexico

Lyal Harris, Ph.D.
Tectonics Special Research Center, Dept. of Geology & Geophysics
University of Western Australia
Perth, Australia

Alexander I. Ioffe, Ph.D.
Senior Scientist, Geological Institute of the Russian Academy of Sciences
Moscow, Russia

David T. King, Jr., Ph.D.
Professor, Dept. of Geology
Auburn University
Auburn, Alabama

Cherry Lewis, Ph.D.
Research Publicity Officer
University of Bristol
Bristol, England, U.K.

Eric v.d. Luft, Ph.D., M.L.S.
Curator of Historical Collections
S.U.N.Y. Upstate Medical University
Syracuse, New York

Jascha Polet, Ph.D.
Research Seismologist, Caltech Seismological Laboratory,
California Institute of Technology
Pasadena, California

Yavor Shopov, Ph.D.
Professor of Geology & Geophysics
University of Sofia
Sofia, Bulgaria

Acknowledgments

In addition to our advisors and contributing advisors, it has been our privilege and honor to work with the following contributing writers and scientists who represent scholarship in the geosciences that spans five continents:

Molly Bell, Ph.D.; Alicia Cafferty; John Cubit, Ph.D.; Laurie Duncan, Ph.D.; John Engle; Agnes Galambosi; Larry Gilman, Ph.D.; David Goings, Ph.D.; Brooke Hall, Ph.D.; William Haneberg, Ph.D.; Michael Lambert; Adrienne Wilmoth Lerner, (Graduate Student, Department of History, Vanderbilt University), Lee Wilmoth Lerner, Jill Liske, M.Ed.; Robert Mahin, Ph.D.; Kelli Miller; William Phillips, Ph.D.; William Rizer, Ph.D.; Jerry Salvadore, Ph.D.; and David Tulloch, Ph.D.

Many of the academic advisors for *World of Earth Science*, along with others, authored specially commissioned articles within their field of expertise. The editors would like to specifically acknowledge the following special contributions:

Cynthia V. Burek, Ph.D.
History of geoscience: Women in the history of geoscience

Nicholas Dittert, Ph.D.
Scientific data management in Earth sciences

William J. Engle. P.E.
Petroleum, economic uses of
Petroleum extraction

G. Thomas Farmer, Ph.D., R.G.
Hydrogeology

Lyal Harris, Ph.D.
Supercontinents

Alexander I. Ioffe, Ph.D.
Bathymetric mapping

David T. King, Jr., Ph.D.
Geologic time
Stratigraphy
Uniformitarianism

Cherry Lewis, Ph.D.
The biography of Author Holmes

Yavor Shopov, Ph.D.
Paleoclimate

The editors wish to gratefully acknowledge Dr. Eric v.d. Luft for his diligent and extensive research related to his compilation of selected biographies for *World of Earth Science*.

The editors also gratefully acknowledge Dr. Yavor Shopov's generous and significant contribution of photographs for *World of Earth Science* and Dr. David King's guidance, comments, and contributions to the introduction.

The editors thank Ms. Kelly Quin and others representing the Gale Imaging Team for their guidance through the complexities and difficulties related to graphics. Last, but certainly not least, the editors thank Mr. Ryan Thomason, whose dedication, energy, and enthusiasm made a substantial difference in the quality of *World of Earth Science*.

Because Earth is theirs to inherit, the editors lovingly dedicate this book to their children, Adrienne, Lee, Amanda, and Adeline. *Per ardua ad astra.*

Cover

The image on the cover depicts an example of several geologic cross sections of strata, illustrating the fundamental laws of geology.

A

AA FLOW • *see* LAVA

ABLATION OF GLACIERS • *see* GLACIATION

ABSOLUTE AGE • *see* DATING METHODS

ABSOLUTE HUMIDITY • *see* HUMIDITY

ABYSSAL PLAINS

Abyssal plains are the vast, flat, sediment-covered areas of the deep ocean floor. They are the flattest, most featureless areas on Earth, and have a slope of less than one foot of elevation difference for each thousand feet of distance. The lack of features is due to a thick blanket of sediment that covers most of the surface.

These flat abyssal plains occur at depths of over 6,500 ft (1,980 m) below sea level. They are underlain by the oceanic **crust**, which is predominantly basalt—a dark, fine-grained volcanic **rock**. Typically, the **basalt** is covered by layers of sediment, much of which is deposited by deep ocean turbidity currents (caused by the greater density of sediment-laden **water**), or biological materials, such as minute shells of marine plants and animals, that have "rained" down from the ocean's upper levels, or a mixture of both.

Other components of abyssal plain sediment include wind-blown dust, volcanic ash, chemical precipitates, and occasional meteorite fragments. Abyssal plains are often littered with nodules of manganese containing varying amounts of **iron**, nickel, cobalt, and **copper**. These pea to potato-sized nodules form by direct **precipitation** of **minerals** from the seawater onto a bone or rock fragment. Currently, deposits of manganese nodules are not being mined from the sea bed, but it is possible that they could be collected and used in the future.

Of the 15 billion tons of river-carried **clay**, **sand**, and gravel that are washed into the **oceans** each year, only a fraction of this amount reaches the abyssal plains. The amount of biological sediment that reaches the bottom is similarly small. Thus, the rate of sediment accumulation on the abyssal plains is very slow, and in many areas, less than an inch of sediment accumulates per thousand years. Because of the slow rate of accumulation and the monotony of the **topography**, abyssal plains were once believed to be a stable, unchanging environment. However, deep ocean currents have been discovered that scour the ocean floor in places. Some currents have damaged trans-oceanic communication cables laid on these plains.

Although they are more common and widespread in the Atlantic and Indian ocean basins than in the Pacific, abyssal plains are found in all major ocean basins. Approximately 40% of the planet's ocean floor is covered by abyssal plains. The remainder of the ocean floor topography consists of hills, cone-shaped or flat-topped mountains, deep trenches, and **mountain chains** such as the mid-oceanic ridge systems.

The abyssal plains do not support a great abundance of aquatic life, though some species do survive in this relatively barren environment. Deep sea dredges have collected specimens of unusual-looking fish, worms, and clam-like creatures from these depths.

See also Deep sea exploration; Ocean trenches

ACID RAIN

Acid rain is rain with a **pH** (a logarithmic measurement of acidity or alkalinity) of less than 5.7. Acid rain usually results from elevated levels of nitric and sulfuric acids in air pollution. Acidic pollutants that can lead to acid rain are common by-products from burning fossil **fuels** (e.g., oil, **coal**, etc.) and are found in high levels in exhaust from internal combustion engines (e.g., automobile exhaust). Acidic **precipitation** may also occur in other forms such as snow.

Acid rain occurs when polluted gasses become trapped in **clouds**. The clouds may drift for hundreds, even thousands, of miles before finally releasing acidic precipitation. Trees, **lakes**, animals, and even buildings are vulnerable to the slow corrosive effects of acid rain, whose damaging components are emitted by power plants and factories, especially those burning low grades of coal and oil.

Acid rain was first recognized in 1872, approximately 100 years after the start of the Industrial Revolution in England, when an English scientist, Robert Angus Smith (1817–1884), pointed out the problem. Almost another century passed, however, before the public became aware of the damaging effects of acid rain. In 1962, the Swedish scientist Svante Oden brought the acid rain quandary to the attention of the press, instead of the less popular scientific journals. He compiled records from the 1950s indicating that acid rain came from air masses moving out of central and western **Europe** into Scandinavia.

After acid rain was discovered in Europe, scientists began measuring the acidity of rain in **North America**. Initially, they found that the problem was concentrated in the northeastern states of New York and Pennsylvania because the type of coal burned there was more sulfuric. By 1980, most of the states east of the Mississippi, as well as southeastern Canada, were receiving acidic rainfall. Acid rain falls in the West also, although the problem is not as severe. Acid rain in Los Angeles, California is caused primarily by local traffic emissions. Car emissions contain nitrogen oxide, the second highest problematic gas in acid rain after sulfur dioxide.

Acid rain is measured through pH tests that determine the concentration of hydrogen ions. Pure **water** has a neutral pH of approximately 7.0. When the pH is greater than 7, the material is thought to be alkaline. At a pH of 5.7, rain is slightly acidic, but when its pH is further reduced, the rain becomes an increasingly stronger acid rain. In the worst cases, acid rain has shown a pH of 2.4 (about as acidic as vinegar). When pH levels are drastically tipped in **soil** and water, entire lakes and **forests** are jeopardized. Evergreen trees in high elevations are especially vulnerable. Although the acid rain itself does not kill the trees, it makes them more susceptible to other dangers. High acid levels in soil causes **leaching** of other valuable **minerals** such as calcium, magnesium, and potassium. According to the World Watch Institute, in the late 1980s and early 1990s forest damage in Europe ranged from a low of 4% in Portugal to a high of 71% in Czechoslovakia, averaging 35% overall.

Small marine organisms cannot survive in acidic lakes and **rivers**, and their depletion affects larger fish and ultimately the entire marine life food chain. Snow from acid rain is also damaging; snowmelt has been known to cause massive, instant death for many kinds of fish. Some lakes in Scandinavia, for example, are completely devoid of fish. Acid rain also eats away at buildings and metal structures. From the Acropolis in Greece to Renaissance buildings in Italy, ancient structures are showing signs of slow **corrosion** from acid rain. In some industrialized parts of Poland, trains cannot exceed 40 miles (65 km) per hour because the **iron** railway tracks have been weakened from acidic air pollution.

New power plants in the United States are being built with strict emissions standards, but retrofitting older plants is difficult and expensive. Nevertheless, the United States Environmental Protection Agency requires most of the older and dirtier power plants to install electrostatic precipitators and baghouse filters—devices designed to remove solid particulates. Such devices are required in Canada, in industrialized countries in Western Europe, and in Japan. Scrubbers, or flue-gas desulfurization technology, are also being used because of their effectiveness in removing as much as 95% of a power plant's sulfur dioxide emissions. These devices are expensive, however, and there are clauses in pollution control laws that allow older plants to continue operation at higher pollution levels. Another way to reduce acid rain is for power plants to burn cleaner coal in their plants. This does not require retrofitting but it does increase transportation costs since coal containing less sulfur is mined in the western part of the United States, far away from where it is needed in the midwest and eastern part of the country.

See also Atmospheric pollution; Erosion; Global warming; Groundwater; Petroleum, economic uses of; Rate factors in geologic processes; Weathering and weathering series

ACTUALISM • *see* UNIFORMITARIANISM

ADAMANTINE

Some transparent **minerals** with very high indices of refraction have a non-metallic, brilliant manner of reflecting and transmitting light called an adamantine luster. **Diamond** is the best-known adamantine mineral, and its coveted sparkle is an example of this type of non-metallic luster. A diamond's internal structure of covalently-bound **carbon** atoms in a three-dimensional matrix causes incident light to refract deeply into the crystal, giving the crystal its characteristic clarity. The isometric, or three-dimensionally symmetrical, crystal structure of diamond also causes light to disperse within the mineral giving cut diamonds their spectral "fire." The synthetic diamond substitute, cubic zirconium, or CZ, has an adamantine luster due to its high index of refraction, but its dispersion, though relatively high, leaves this copy without the fire of the real diamond.

The index of refraction, n, for a given material is the ratio between the velocity of light in air, and its velocity in a denser material. Snell's law defines the precise relationship between the angle of incidence (i), and the angle of refraction (r), as $\sin i/\sin r=n$, where n is again the index of refraction. Non-metallic minerals with tightly bound, tightly packed atoms in a strong three-dimensional crystal lattice are more likely to have a high index of refraction. They are also more likely to be very hard and to have an adamantine luster. The mineral corundum, whose colored varieties include the **gemstones** ruby and sapphire, has a hardness of nine on the Moh's scale and a vitreous to adamantine luster. The **lead** carbonate mineral, cerussite, and lead sulfate mineral, anglesite, also have adamantine lusters.

See also Crystals and crystallography

ADIABATIC HEATING

Adiabatic processes are those in which there is no net heat transfer between a system and its surrounding environment (e.g., the product of pressure and volume remains constant). Because it is a gas, air undergoes adiabatic heating and cooling as it experiences **atmospheric pressure** changes associated with changing altitudes. Increasing pressure adiabatically heats air masses, falling pressures allow air to expand and cool.

Adiabatic heating and cooling is common in convective atmospheric currents. In adiabatic heating and cooling there is no net transfer of mass or thermal exchange between the system (e.g., volume of air) the external or surrounding environment. Accordingly, the change in **temperature** of the air mass is due to internal changes.

In adiabatic cooling, when a mass of air rises—as it does when it moves upslope against a mountain range—it encounters decreasing atmospheric pressure with increasing elevation. The air mass expands until it reaches pressure equilibrium with the external environment. The expansion results in a cooling of the air mass.

With adiabatic heating, as a mass of air descends in the atmosphere—as it does when it moves downslope from a mountain range—the air encounters increasing atmospheric pressure. Compression of the air mass is accompanied by an increase in temperature.

Because warmer air is less dense than cooler air, warmer air rises. Counter-intuitively, moist air is also lighter than less humid air. The **water**, composed of the elements of **oxygen** and hydrogen is lighter than dominant atmospheric elements of oxygen and nitrogen. For this reason, warm moist air rises and contributes to atmospheric instability.

In the lower regions of the atmosphere (up to altitudes of approximately 40,000 feet [12,192 m]), temperature decreases with altitude at the **atmospheric lapse rate**. Because the atmosphere is warmed by conduction from Earth's surface, this lapse or reduction in temperature normal with increasing distance from the conductive source. The measurable lapse rate is affected by the relative **humidity** of an air mass. Unsaturated or dry air changes temperature at an average rate 5.5°F (3.05°C) per 1,000 feet (304 m). Saturated air—defined as air at 100% relative humidity—changes temperature by an average of 3°F (1.66°C) per 1,000 feet (304 m). These average lapse rates can be used to calculate the temperature changes in air undergoing adiabatic expansion and compression.

For example, as an air mass at 80% relative humidity (dry air) at 65°F (18.3° C) rises up the side of a mountain chain from sea level it will decrease in temperature at rate of 5.5°F (3.05°C) per 1,000 feet (304 m) until the changing temperature changes the relative humidity (a measure of the moisture capacity of air) to 100%. In addition to cloud formation and **precipitation**, the continued ascension of this now "wet'' or saturated air mass proceeds at 3°F (1.66°C) per 1,000 feet (304 m). If the saturation point (the point at which "dry" air becomes "wet" air) is at 4,000 feet (1,219 m), the hypothetical air mass starting at 65°F (18.3°C) would cool 22°F (12.2°C) to 43°F (6.1°C) at an altitude of 4,000 feet (1,219 m). If the air ascended another 6,000 feet (1,829 m) to the top of the mountain chain before starting downslope, the temperature at the highest elevation of 10,000 feet (3,048 m) would measure 25°F (–3.9°C). This accounts for precipitation in the form of snow near mountain peaks even when valley temperatures are well above **freezing**. Because the absolute moisture content of the air mass has been reduced by cloud formation and precipitation, as the air moves downslope and warms it quickly falls below saturation and therefore heats at the dry lapse rate of 5.5°F (3.05°C) per 1,000 feet (304 m). A dry air mass descending 10,000 feet (3,048 m) would increase in temperature by 55°F (30.6°C). In the example given, the hypothetical air mass starting upslope at 65°F (18.3°C), rising 10,000 feet (3,048 m) and then descending 10,000 feet (3,048 m) would measure 80°F (26.7°C) at sea level on the other side of the mountain chain.

Although actual lapse rates do not strictly follow these guidelines, they present a model sufficiently accurate to predict temperate changes. The differential wet/dry lapse rates can result in the formation of hot downslope winds (e.g., Chinook winds, Santa Anna winds, etc).

See also Air masses and fronts; Land and sea breeze; Seasonal winds

ADVECTION

Earth's atmosphere is a dynamic sea of gases in constant motion and Earth's **oceans** contain currents that move **water** across the globe. Advection is a lateral or horizontal transfer of mass, heat, or other property. Accordingly, winds that blow across Earth's surface represent advectional movements of air. Advection also takes place in the ocean in the form of currents. Currently, geologists debate the presence and role of substantial advective processes in Earth's mantle.

Differential pressures and temperatures drive the **mass movement** of air seeking equilibrium (the lowest energy state). Advective winds move from areas of higher **temperature** toward areas of lower temperature. In contrast, convection, the vertical movement of mass or transfer of heat, manifests itself as air currents. Accordingly, winds are a result of advection, while air currents are a result of convection.

Although in a gaseous state, the atmosphere observes fluid-like dynamics. This is an important consideration when considering advection, because advection is usually more pronounced in the movement of fluids. For example, advection also takes place in the oceans where advection is broadened to include the lateral (horizontal) transfer of not only fluid mass and heat, but of other properties such and **oxygen** content and salinity.

In the atmosphere, advection is the sole process of lateral transfer of mass. In contrast, vertical transfer occurs via conduction, convection, and radiation. Just as ocean currents permit heat transfer from areas of warm water to an **area** of water with cooler temperatures, advective winds allow the transfer of both sensible heat and latent heat (a function of **humidity**).

Although advection processes are important heat equilibration mechanisms for both the atmosphere and the oceans, the speed and volume of mass transported differs greatly between the atmosphere and oceans. The magnitude of heat transference depends on heat flux (the rate of heat transport), and flux in turn relates the transfer of heat energy in terms of area and time. Both processes contribute approximately equally because **wind** currents are much faster (higher rate) than ocean currents but ocean currents move substantially denser masses of molecules.

Advection is also responsible for the formation of advection **fog**. Advection fog usually occurs when the atmosphere is very stable so that moist (humid) air near the surface does not mix vertically with an overlying layer of drier air. The advection fog forms as warm and moist air moves horizontally along the cooler surface and the air near the surface is cooled to its **dew point**.

See also Adiabatic heating; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pressure; Convection (updrafts and downdrafts); Insolation and total solar irradiation; Wind chill; Wind shear

ADVECTIONAL FOG • *see* FOG

AERODYNAMICS

Aerodynamics is the science of airflow over airplanes, cars, buildings, and other objects. Aerodynamic principles are used to find the best ways in which airplanes produce lift, reduce drag, and remain stable (by controlling the shape and size of the wing, the angle at which it is positioned with respect to the airstream, and the flight speed). The flight characteristics change at higher altitudes as the surrounding air becomes colder and thinner. The behavior of the airflow also changes dramatically at flight speeds close to, and beyond, the speed of sound. The explosion in computational capability has made it possible to understand and exploit the concepts of aerodynamics and to design improved wings for airplanes. Increasingly sophisticated **wind** tunnels are also available to test new models.

Airflow is governed by the principles of fluid dynamics that deal with the motion of liquids and gases in and around solid surfaces. The viscosity, density, compressibility, and **temperature** of the air determine how the air will flow around a building or a plane. The viscosity of a fluid is its resistance to flow. Even though air is 55 times less viscous than **water**, viscosity is important near a solid surface because air, like all other fluids, tends to stick to the surface and slow down the flow. A fluid is compressible if its density can be increased by squeezing it into a smaller volume. At flow speeds less than 220 mph (354 kph), one third the speed of sound, we can assume that air is incompressible for all practical purposes. At speeds closer to that of sound (660 mph [1,622 kph]) however, the variation in the density of the air must be taken into account. The effects of temperature change also become important at these speeds. A regular commercial airplane, after landing, will feel cool to the touch. The Concorde jet, which flies at twice the speed of sound, can feel hotter than boiling water.

Flow patterns of the air may be laminar or turbulent. In laminar or streamlined flow, air, at any point in the flow, moves with the same speed in the same direction at all times so that smoke in the flow appears to be smooth and regular. The smoke then changes to turbulent flow, which is cloudy and irregular, with the air continually changing speed and direction.

Laminar flow, without viscosity, is governed by **Bernoulli's principle** that states that the sum of the static and dynamic pressures in a fluid remains the same. A fluid at rest in a pipe exerts static pressure on the walls. If the fluid starts moving, some of the static pressure is converted to dynamic pressure, which is proportional to the square of the speed of the fluid. The faster a fluid moves, the greater its dynamic pressure and the smaller the static pressure it exerts on the sides.

Bernoulli's principle works very well far from the surface. Near the surface, however, the effects of viscosity must be considered since the air tends to stick to the surface, slowing down the flow nearby. Thus, a boundary layer of slow-moving air is formed on the surface of an airplane or automobile. This boundary layer is laminar at the beginning of the flow, but it gets thicker as the air moves along the surface and becomes turbulent after a point.

Airflow is determined by many factors, all of which work together in complicated ways to influence flow. Very often, the effects of factors such as viscosity, speed, and turbulence cannot be separated. Engineers have found ingenious ways to get around the difficulty of treating such complex situations. They have defined some characteristic numbers, each of which tells us something useful about the nature of the flow by taking several different factors into account.

One such number is the Reynolds number, which is greater for faster flows and denser fluids and smaller for more viscous fluids. The Reynolds number is also higher for flow around larger objects. Flows at lower Reynolds numbers tend to be slow, viscous, and laminar. As the Reynolds number increases, there is a transition from laminar to turbulent flow. The Reynolds number is a useful similarity parameter. This means that flows in completely different situations will behave in the same way as long as the Reynolds number and the shape of the solid surface are the same. If the Reynolds number is kept the same, water moving around a small stationary airplane model will create exactly the same flow patterns as a full-scale airplane of the same shape, flying through the air. This principle makes it possible to test airplane and automobile designs using small-scale models in wind tunnels.

At speeds greater than 220 mph (354 kph), the compressibility of air cannot be ignored. At these speeds, two different flows may not be equivalent even if they have the same Reynolds number. Another similarity parameter, the Mach number, is needed to make them similar. The Mach number of an airplane is its flight speed divided by the speed of sound at the same altitude and temperature. This means that a plane flying at the speed of sound has a Mach number of one.

The drag coefficient and the lift coefficient are two numbers that are used to compare the forces in different flow situations. Aerodynamic drag is the force that opposes the motion of a car or an airplane. Lift is the upward force that keeps an airplane afloat against **gravity**. The drag or lift coefficient is defined as the drag or lift force divided by the dynamic pressure, and also by the **area** over which the force acts. Two objects with similar drag or lift coefficients experience comparable forces, even when the actual values of the drag or lift force, dynamic pressure, area, and shape are different in the two cases.

There are several sources of drag. The air that sticks to the surface of a car creates a drag force due to skin friction. Pressure drag is created when the shape of the surface changes abruptly, as at the point where the roof of an automobile ends. The drop from the roof increases the **space** through which the air stream flows. This slows down the flow and, by Bernoulli's principle, increases the static pressure. The air stream is unable to flow against this sudden increase in pressure and the boundary layer gets detached from the surface creating an area of low-pressure turbulent wake or flow. Because the pressure in the wake is much lower than the pressure in front of the car, a net backward drag or force is exerted on the car. Pressure drag is the major source of drag on blunt bodies. Car manufacturers experiment with vehicle shapes to minimize the drag. For smooth or "streamlined" shapes, the boundary layer remains attached longer, producing only a small wake. For such bodies, skin friction is the major source of drag, especially if they have large surface areas. Skin friction comprises almost 60% of the drag on a modern airliner.

An airfoil is the two-dimensional cross-section of the wing of an airplane as one looks at it from the side. It is designed to maximize lift and minimize drag. The upper surface of a typical airfoil has a curvature greater than that of the lower surface. This extra curvature is known as camber. The straight line, joining the front tip or the leading edge of the airfoil to the rear tip or the trailing edge, is known as the chord line. The angle of attack is the angle that the chord line forms with the direction of the air stream.

The stagnation point is the point at which the stream of air moving toward the wing divides into two streams, one flowing above and the other flowing below the wing. Air flows faster above a wing with greater camber since the same amount of air has to flow through a narrower space. According to Bernoulli's principle, the faster flowing air exerts less pressure on the top surface, so that the pressure on the lower surface is higher, and there is a net upward force on the wing, creating lift. The camber is varied, using flaps and slats on the wing in order to achieve different degrees of lift during takeoff, cruise, and landing.

Because the air flows at different speeds above and below the wing, a large jump in speed will tend to arise when the two flows meet at the trailing edge, leading to a rearward stagnation point on top of the wing. Wilhelm Kutta (1867–1944) discovered that a circulation of air around the wing would ensure smooth flow at the trailing edge. According to the Kutta condition, the strength of the circulation, or the speed of the air around the wing, is exactly as much as is needed to keep the flow smooth at the trailing edge.

Increasing the angle of attack moves the stagnation point down from the leading edge along the lower surface so that the effective area of the upper surface is increased. This results in a higher lift force on the wing. If the angle is increased too much, however, the boundary layer is detached from the surface, causing a sudden loss of lift. This is known as a stall; the angle at which this occurs for an airfoil of a particular shape is known as the stall angle.

The airfoil is a two-dimensional section of the wing. The length of the wing in the third dimension, out to the side, is known as the span of the wing. At the wing tip at the end of the span, the high-pressure flow below the wing meets the low-pressure flow above the wing, causing air to move up and around in wing-tip vortices. These vortices are shed as the plane moves forward, creating a downward force or downwash behind it. The downwash makes the airstream tilt downward and the resulting lift force tilt backward so that a net backward force or drag is created on the wing. This is known as induced drag or drag due to lift. About one third of the drag on a modern airliner is induced drag.

In addition to lift and drag, the stability and control of an aircraft in all three dimensions is important since an aircraft, unlike a car, is completely surrounded by air. Various control devices on the tail and wing are used to achieve this. Ailerons, for instance, control rolling motion by increasing lift on one wing and decreasing lift on the other.

Flight at speeds greater than that of sound are supersonic. Near a Mach number of one, some portions of the flow are at speeds below that of sound, while other portions move faster than sound. The range of speeds from Mach number 0.8 to 1.2 is known as transonic. Flight at Mach numbers greater than five is hypersonic.

The compressibility of air becomes an important aerodynamic factor at these high speeds. The reason for this is that sound waves are transmitted through the successive compression and expansion of air. The compression due to a sound wave from a supersonic aircraft does not have a chance to get away before the next compression begins. This pile up of compression creates a shock wave, which is an abrupt change in pressure, density, and temperature. The shock wave causes a steep increase in the drag and loss of stability of the aircraft. Drag due to the shock wave is known as wave drag. The familiar "sonic boom" is heard when the shock wave touches the surface of the earth.

Temperature effects also become important at transonic speeds. At hypersonic speeds above a Mach number of five, the heat causes nitrogen and **oxygen** molecules in the air to break up into atoms and form new compounds by chemical reactions. This changes the behavior of the air and the simple laws relating pressure, density, and temperature become invalid.

The need to overcome the effects of shock waves has been a formidable problem. Swept-back wings have helped to reduce the effects of shock. The supersonic Concorde that cruises at Mach 2 and several military airplanes have **delta** or triangular wings. The supercritical airfoil designed by Richard Whitcomb of the NASA Langley Laboratory has made air flow around the wing much smoother and has greatly improved both the lift and drag at transonic speeds. It has only a slight curvature at the top and a thin trailing edge. The proposed hypersonic aerospace plane is expected to fly partly in air and partly in space and to travel from Washington to Tokyo within two hours. The challenge for aerodynamicists is to control the flight of the aircraft so that it does not burn up like a meteor as it returns to Earth at several times the speed of sound.

See also Atmosphere; Atmospheric circulation; Atmospheric composition and structure; Atmospheric pressure; Aviation physiology; Bernoulli's equation; Meteorology; Physics; Space physiology; Wind shear

AEROMAGNETICS • *see* MAPPING TECHNIQUES

AFRICA

From the perspective of geologists and paleontologists, Africa takes center stage in the physical history and development of life on Earth. Africa is the world's second largest continent. Africa possesses the world's richest and most concentrated deposits of **minerals** such as gold, diamonds, uranium, chromium, cobalt, and platinum. It is also the cradle of human **evolution** and the birthplace of many animal and plant species, and has the earliest evidence of reptiles, dinosaurs, and mammals.

Present-day Africa, occupying one-fifth of Earth's land surface, is the central remnant of the ancient southern supercontinent called Gondwanaland, a landmass once made up of **South America**, **Australia**, **Antarctica**, India, and Africa. This massive supercontinent broke apart between 195 million and 135 million years ago, cleaved by the same geological forces that continue to transform Earth's **crust** today.

Plate tectonics are responsible for the rise of mountain ranges, the gradual drift of continents, earthquakes, and **volcanic eruptions**. The fracturing of Gondwanaland took place during the **Jurassic Period**, the middle segment of the **Mesozoic Era** when dinosaurs flourished on Earth. It was during the Jurassic that flowers made their first appearance, and dinosaurs like the carnivorous Allosaurus and plant eating Stegasaurus lived.

Geologically, Africa is 3.8 billion years old, which means that in its present form or joined with other continents as it was in the past, Africa has existed for four-fifths of Earth's 4.6 billion years. Africa's age and geological continuity are unique among continents. Structurally, Africa is composed of five cratons (structurally stable, undeformed regions of Earth's crust). These cratons, in south, central, and west Africa are mostly igneous **granite**, **gneiss**, and **basalt**, and formed separately between 3.6 and 2 billion years ago, during the **Precambrian** Era.

The Precambrian, an era which comprises more than 85% of the planet's history, was when life first evolved and the earth's atmosphere and continents developed. Geochemical analysis of undisturbed African rocks dating back 2 billion years has enabled paleoclimatologists to determine that Earth's atmosphere contained much higher levels of **oxygen** than today.

Africa, like other continents, "floats" on a plastic layer of Earth's upper mantle called the **asthenosphere**. The overlying rigid crust or **lithosphere** can be as thick as 150 mi (240 km) or under 10 mi (16 km), depending on location. The continent of Africa sits on the African plate, a section of the earth's crust bounded by mid-oceanic ridges in the Atlantic and Indian **Oceans**. The entire plate is creeping slowly toward the northwest at a rate of about 0.75 in (2 cm) per year.

The African plate is also spreading or moving outward in all directions, and therefore Africa is growing in size. Geologists state that sometime in the next 50 million years, East Africa will split off from the rest of the continent along the East African rift which stretches 4,000 mi (6,400 km) from the Red Sea in the north to Mozambique in the south.

Considering its vast size, Africa has few extensive mountain ranges and fewer high peaks than any other continent. The major ranges are the Atlas Mountains along the northwest coast and the Cape ranges in South Africa. Lowland plains are also less common than on other continents.

Geologists characterize Africa's **topography** as an assemblage of swells and basins. Swells are **rock** strata warped upward by heat and pressure, while basins are masses of lower lying crustal surfaces between swells. The swells are highest in East and central West Africa where they are capped by volcanic flows originating from the seismically active East African rift system. The continent can be visualized as an uneven tilted plateau, one that slants down toward the north and east from higher elevations in the west and south.

During much of the **Cretaceous Period**, from 130 million to 65 million years ago, when dinosaurs like tyrannosaurus, brontosaurus, and triceratops walked the earth, Africa's coastal areas and most of the Sahara **Desert** were submerged underwater. **Global warming** during the Cretaceous Period melted **polar ice** and caused ocean levels to rise. Oceanic organic sediments from this period were transformed into the **petroleum** and **natural gas** deposits now exploited by Libya, Algeria, Nigeria, and Gabon. Today, oil and natural gas drilling is conducted both on land and offshore on the **continental shelf**.

The continent's considerable geological age has allowed more than enough time for widespread and repeated **erosion**, yielding soils leached of organic nutrients but rich in **iron** and **aluminum** oxides. Such soils are high in mineral deposits such as bauxite (aluminum ore), manganese, iron, and gold, but they are very poor for agriculture. Nutrient-poor **soil**, along with deforestation and desertification (expansion of deserts) are just some of the daunting challenges facing African agriculture in modern times.

The most distinctive and dramatic geological feature in Africa is undoubtedly the East African rift system. The rift opened up in the **Tertiary Period**, approximately 65 million years ago, shortly after the dinosaurs became extinct. The same tectonic forces that formed the rift valley and which threaten to eventually split East Africa from the rest of the continent have caused the northeast drifting of the Arabian plate, the opening of the Red Sea to the Indian Ocean, and the volcanic uplifting of Africa's highest peaks including its highest, Kilimanjaro in Tanzania. Mount Kibo, the higher of Kilimanjaro's two peaks, soars 19,320 ft (5,796 m) and is permanently snowcapped despite its location near the equator.

Both Kilimanjaro and Africa's second highest peak, Mount Kenya (17,058 ft; 5,117 m) sitting astride the equator, are actually composite volcanos, part of the vast volcanic field associated with the East African rift valley. The rift valley is also punctuated by a string of **lakes**, the deepest being Lake Tanganyika with a maximum depth of 4,708 ft (1,412 m). Only Lake Baikal in Eastern Russia is deeper at 5,712 ft (1,714 m).

Seismically, the rift valley is very much alive. **Lava** flows and volcanic eruptions occur about once a decade in the Virunga Mountains north of Lake Kivu along the western stretch of the rift valley. One **volcano** in the Virunga **area** in eastern Zaire which borders Rwanda and Uganda actually dammed a portion of the valley formerly drained by a tributary of the Nile River, forming Lake Kivu as a result.

On its northern reach, the 4,000-mi (6,400-km) long rift valley separates Africa from **Asia**. The rift's eastern arm can be traced from the Gulf of Aqaba separating Arabia from the Sinai Peninsula, down along the Red Sea, which divides Africa from Arabia. The East African rift's grabens (basins of crust bounded by fault lines) stretch through the extensive highlands of central Ethiopia which range up to 15,000 ft (4,500 m) and then along the Awash River. Proceeding south, the rift valley is dotted by a series of small lakes from Lake Azai to Lake Abaya and then into Kenya by way of Lake Turkana.

Slicing through Kenya, the rift's grabens are studded by another series of small lakes from Lake Baringo to Lake Magadi. The valley's trough or basin is disguised by layers of volcanic ash and other sediments as it threads through Tanzania via Lake Natron. However, the rift can be clearly discerned again in the elongated shape of Lake Malawi and the Shire River Valley, where it finally terminates along the lower Zambezi River and the Indian Ocean near Beira in Mozambique.

The rift valley also has a western arm which begins north of Lake Mobutu along the Zaire-Uganda border and continues to Lake Edward. It then curves south along Zaire's eastern borders forming that country's boundaries with Burundi as it passes through Lake Kivu and Tanzania by way of Lake Tanganyika.

The rift's western arm then extends toward Lake Nysasa (Lake Malawi). Shallow but vast, Lake Victoria sits in a trough between the rift's two arms. Although the surface altitude of the rift valley lakes like Nyasa and Tanganyika are hundreds of feet above sea level, their floors are hundreds of feet below due to their great depths.

The eastern arm of the rift valley is much more active than the western branch, volcanically and seismically. There are more volcanic eruptions in the crust of the eastern arm with intrusions of **magma** (subterranean molten rock) in the middle and lower crustal depths. Geologists consider the geological forces driving the eastern arm to be those associated with the origin of the entire rift valley and deem the eastern arm to be the older of the two.

It was in the great African rift valley that hominids, or human ancestors, arose. Hominid **fossils** of the genus *Australopithicus* dating 3–4 million years ago have been unearthed in Ethiopia and Tanzania. And the remains of a more direct ancestor of man, *Homo erectus*, who was using fire 500,000 years ago, have been found in Olduvai Gorge in Tanzania as well as in Morocco, Algeria, and Chad.

Paleontologists, who study fossil remains, employ radioisotope dating techniques to determine the age of hominid and other species' fossil remains. This technique measures the decay of short-lived radioactive isotopes like **carbon** and argon to determine a fossil's age. This is based on the radioscope's atomic **half-life**, or the time required for half of a sample of a radioisotope to undergo radioactive decay. Dating is typically done on volcanic ash layers and charred wood associated with hominid fossils rather than the fossils themselves, which usually do not contain significant amounts of radioactive isotopes.

Present-day volcanic activity in Africa is centered in and around the East African rift valley. Volcanoes are found in Tanzania at Oldoinyo Lengai and in the Virunga range on the Zaire-Uganda border at Nyamlagira and Nyiragongo. There is also volcanism in West Africa. Mount Cameroon (13,350 ft; 4,005 m) along with smaller volcanos in its vicinity, stand on the bend of Africa's West Coast in the Gulf of Guinea, and are the exception. They are the only active volcanoes on the African mainland not in the rift valley.

However, extinct volcanoes and evidence of their activity are widespread on the continent. The Ahaggar Mountains in the central Sahara contain more than 300 volcanic necks that rise above their surroundings in vertical columns of 1,000 ft or more. Also, in the central Sahara, several hundred miles to the east in the Tibesti Mountains, there exist huge volcanic craters or calderas. The Trou au Natron is 5 mi (8 km) wide and over 3,000 ft (900 m) deep. In the rift valley, the Ngorongoro Crater in Tanzania, surrounded by teeming wildlife and spectacular scenery, is a popular tourist attraction. Volcanism formed the diamonds found in South Africa and Zaire. The Kimberly **diamond** mine in South Africa is actually an ancient volcanic neck.

The only folded mountains in Africa are found at the northern and southern reaches of the continent. Folded mountains result from the deformation and uplift of the earth's crust, followed by deep erosion. Over millions of years this process built ranges like the Atlas Mountains, which stretch from Morocco to Algeria and Tunisia.

Geologically, the Atlas Mountains are the southern tangent of the European Alps, geographically separated by the

Strait of Gibraltar in the west and the Strait of Sicily in the east. The Atlas are strung across northwest Africa in three parallel arrays; the coastal, central, and Saharan ranges. By trapping moisture, the Atlas Mountains carve out an oasis along a strip of northwest Africa compared with the dry and inhospitable Sahara Desert just to the south.

The Atlas Mountains are relatively complex folded mountains featuring horizontal thrust faults and ancient crystalline cores. On the other hand, the Cape ranges are older, simpler structures, analogous in age and erosion to the Appalachian Mountains of the eastern United States. The Cape ranges rise in a series of steps from the ocean to the interior, flattening out in plateaus and rising again to the next ripple of mountains.

For a continent of its size, Africa has very few islands lying off its coast. The major Mediterranean islands of Corsica, Sardinia, Sicily, Crete, and Cyprus owe their origins to the events that formed Europe's Alps, and are a part of the Eurasian plate, not Africa. Islands lying off Africa's Atlantic Coast like the Canaries, Azores, and even the Cape Verde Islands near North Africa are considered Atlantic structures. Two islands in the middle of the South Atlantic, Ascension and St. Helena, also belong to the Atlantic. Islands belonging to Equatorial Guinea as well as the island country of Sao Tome and Principe at the sharp bend of Africa off of Cameroon and Gabon are related to volcanic peaks of the Cameroon Mountains, the principal one being Mount Cameroon.

Madagascar, the world's fourth largest island after Greenland, New Guinea, and Borneo, is a geological part of ancient Gondwanaland. The island's eastern two-thirds are composed of crystalline **igneous rocks**, while the western third is largely sedimentary. Although volcanism is now quiescent on the island, vast lava flows indicate widespread past volcanic activity. Madagascar's unique plant and animal species testify to the island's long separation from the mainland.

Marine fossils, notably tribolites dating from the **Cambrian Period** (505–570 million years ago; the first period of the **Paleozoic Era**) have been found in southern Morocco and Mauritania. Rocks from the succeeding period, the Ordovician (500–425 million years ago) consist of sandstones with a variety of fossilized marine organisms; these rocks occur throughout northern and western Africa, including the Sahara.

The Ordovician Period was characterized by the development of brachiopods (shellfish similar to clams), corals, starfish, and some organisms that have no modern counterparts, called sea scorpions, conodonts, and graptolites. At the same time, the African crust was extensively deformed. The continental table of the central and western Sahara was lifted up almost a mile (1.6 km). The uplifting alternated with crustal subsidings, forming valleys that were periodically flooded.

During the **Ordovician Period**, Africa, then part of Gondwanaland, was situated in the southern hemisphere on or near the South Pole. It was toward the end of this period that huge **glaciers** formed across the present-day Sahara and the valleys were filled by **sandstone** and glacial deposits. Although Africa today sits astride the tropics, it was once the theater of the Earth's most spectacular glacial activity. In the next period, the Silurian (425–395 million years ago), further marine sediments were deposited.

The Silurian was followed by the Devonian, Mississippian, and Pennsylvanian Periods (408–286 million years ago), the time interval when insects, reptiles, amphibians, and **forests** first appeared. A continental collision between Africa (Gondwanaland) and the North American plate formed a super-supercontinent (Pangaea) and raised the ancient Mauritanide mountain chain that once stretched from Morocco to Senegal. During the late **Pennsylvanian Period**, layer upon layer of fossilized plants were deposited, forming seams of **coal** in Morocco and Algeria.

When Pangaea and later Gondwanaland split apart in the Cretaceous Period (144–66 million years ago), a shallow sea covered much of the northern Sahara and Egypt as far south as the Sudan. Arabia, subjected to many of the same geological and climatic influences as northern Africa, was thrust northward by tectonic movements at the end of the Oligocene and beginning of the Miocene Epochs (around 30 million years ago). During the Oligocene and Miocene (5–35 million years ago; segments of the modern **Cenozoic Era**) bears, monkeys, deer, pigs, dolphins, and early apes first appeared.

Arabia at this time nearly broke away from Africa. The Mediterranean swept into the resulting rift, forming a gulf that was plugged by an isthmus at present-day Aden on the Arabian Peninsula and Djibouti near Ethiopia. This gulf had the exact opposite configuration of today's Red Sea, which is filled by waters of the Indian Ocean.

As the **Miocene Epoch** ended about five million years ago, the isthmus of Suez was formed and the gulf (today's Red Sea) became a saline (salty) lake. During the Pliocene (1.6–5 million years ago) the Djibouti-Aden isthmus subsided, permitting the Indian Ocean to flow into the rift that is now the Red Sea.

In the **Pleistocene Epoch** (11,000–1.6 million years ago), the Sahara was subjected to humid and then to dry and arid phases, spreading the Sahara desert into adjacent forests and green areas. About 5,000–6,000 years ago in the post glacial period of the modern epoch, the Holocene, a further succession of dry and humid stages, further promoted desertification in the Sahara as well as the Kalahari in southern Africa.

Earth scientists state the expansion of the Sahara is still very much in evidence today, causing the desertification of farm and grazing land and presenting the omnipresent specter of famine in the Sahel (Saharan) region.

Africa has the world's richest concentration of minerals and gems. In South Africa, the Bushveld Complex, one of the largest masses of igneous rock on Earth, contains major deposits of strategic **metals** such as platinum, chromium, and vanadium—metals that are indispensable in tool making and high tech industrial processes. The Bushveld complex is about 2 billion years old.

Another spectacular intrusion of magmatic rocks composed of **olivine**, augite, and hypersthene occurred in the **Archean** Eon over 2.5 billion years ago in Zimbabwe. Called the Great Dyke, it contains substantial deposits of chromium, asbestos, and nickel. Almost all of the world's chromium reserves are found in Africa. Chromium is used to harden alloys, to produce stainless steels, as an industrial catalyst, and to provide **corrosion** resistance.

Unique eruptions that occurred during the Cretaceous in southern and central Africa formed kimberlite pipes—vertical, near-cylindrical rock bodies caused by deep **melting** in the upper mantle. Kimberlite pipes are the main source of gem and industrial diamonds in Africa. Africa contains 40% of the world's diamond reserves, which occur in South Africa, Botswana, Namibia, Angola, and Zaire.

In South Africa, uranium is found side-by-side with gold, thus decreasing costs of production. Uranium deposits are also found in Niger, Gabon, Zaire, and Namibia. South Africa alone contains half the world's gold reserves. Mineral deposits of gold also occur in Zimbabwe, Zaire, and Ghana. Alluvial gold (eroded from soils and rock strata by **rivers**) can be found in Burundi, Côte d'Ivoire, and Gabon.

As for other minerals, half of the world's cobalt is in Zaire and a continuation into Zimbabwe of Zairian cobalt-bearing geological formations gives the former country sizable reserves of cobalt as well. One quarter of the world's aluminum ore is found in a coastal belt of West Africa stretching 1,200 mi (1,920 km) from Guinea to Togo, with the largest reserves in Guinea.

Major coal deposits exist in southern Africa, North Africa, Zaire, and Nigeria. North Africa is awash in petroleum reserves, particularly in Libya, Algeria, Egypt, and Tunisia. Nigeria is the biggest petroleum producer in West Africa, but Cameroon, Gabon, and the Congo also contain oil reserves. There are also petroleum reserves in southern Africa, chiefly in Angola.

Most of Africa's iron reserves are in western Africa, with the most significant deposits in and around Liberia, Guinea, Gabon, Nigeria, and Mauritania. In West Africa as well as in South Africa where iron deposits are also found, the ore is bound up in Precambrian rock strata.

Africa, like other continents, has been subjected to gyrating swings in **climate** during the Quartenary Period of the last 2 million years. These climatic changes have had dramatic affects on **landforms** and vegetation. Some of these cyclical changes may have been driven by cosmic or astronomical phenomena including asteroid and comet collisions.

But the impact of humankind upon the African environment has been radical and undeniable. Beginning 2,000 years ago and accelerating to the present day, African woodland belts have been deforested. Such environmental degradation has been exacerbated by overgrazing, agricultural abuse, and man-made changes, including possible global warming partially caused by the buildup of man-made **carbon dioxide**, chlorofluorocarbons (CFCs), and other **greenhouse gases**.

Deforestation, desertification, and soil erosion pose threats to Africa's man-made lakes and thereby Africa's hydroelectric capacity. Africa's multiplying and undernourished populations exert ever greater demands on irrigated agriculture, but the continent's **water** resources are increasingly taxed beyond their limits. To stabilize Africa's ecology and safeguard its resources and mineral wealth, many earth scientists argue that greater use must be made of sustainable agricultural and pastoral practices. Progress in environmental and resource management, as well as population control is also vital.

See also Earth (planet)

AGASSIZ, LOUIS (1807-1873)

Swiss-born American naturalist

Jean Louis Rodolphe Agassiz was born in Motieren-Vuly, Switzerland, and grew up appreciating the beauty of the Swiss Alps. Agassiz's childhood was supervised by his minister father, who believed that supernatural powers created all natural wonders. Agassiz followed his family's wishes and pursued a degree in medicine. After attending the universities in Munich and Heidelberg, Germany, and Zurich, Switzerland, he eventually earned his Ph.D. in 1829.

Upon his graduation from the University of Munich, Agassiz published a monograph on the fish of Brazil that sparked the attention of the noted French anatomist **Georges Cuvier**. Although he possessed a strong interest in zoology, Agassiz went on to earn a medical degree. In 1832, he went to Paris to serve as an apprentice to Cuvier during that renowned scientist's last years.

Agassiz then accepted his first professional position as a professor of natural history at Neuchatel in Switzerland. For his first project, he published a five-volume work on fossil fish. This work helped establish his reputation as a naturalist and earned him the Wollaston Prize.

Agassiz then shifted his attention to the study of **glaciers**. Among many others, Agassiz was fascinated with the extreme heights of the Alps and the occasional sight of huge boulders that were thought to have been created by glacial movement. He spent his vacations in 1836 and 1837 exploring the glacial formations of Switzerland and compared them with the **geology** of England and central **Europe**.

The question of whether or not glaciers moved intrigued Agassiz, who discovered the answer in 1839 at a cabin that had been built on a glacier approximately 10 years earlier. In one decade it had moved nearly 1 mi (1.6 km) down the glacier from its original site. In a unique experiment, Agassiz drove a straight line of stakes deeply into the **ice** across the glacierhill and then observed their movement. After moving, the stakes formed a U shape as middle stakes had moved more quickly than the side ones. Agassiz concluded that the center stakes moved faster since the glacier was held back at the edges by friction with the mountain wall.

This experiment demonstrated not only that glacier moved, but that many thousands of years before massive ice blocks had probably moved across a great deal of the European land masses that now lacked the massive ice formations. The resulting conclusions led to the term Ice Age, which purported that glacial movement is responsible for modern geological configurations. One of the most significant developments that came out of his observations resulted when his discovery helped provide answers to studies pursued by such naturalists as **Charles Darwin** and **Charles Lyell**.

These two men concluded that **glaciation** was a primary mechanism in causing the geographical distribution and apparent similarities of flora and fauna that were otherwise inexplicably separated by land and **water** masses. Despite the evidence with which he was presented, Agassiz's background prevented him from agreeing with such conclusions, and he continued to believe that supernatural forces were responsible for the similarities.

See also Glacial landforms; Ice ages

AGRICOLA, GEORGIUS (1494-1555)

German physician and geologist

Georgius Agricola was born Georg Bauer, but later Latinized his name to Georgius Agricola, as was the custom of the time. (The German word bauer and the Latin word agricola both mean farmer.) His research and publications on a wide range of geologic topics, including **mineralogy**, paleontology, **stratigraphy**, mountains, earthquakes, volcanoes, and **fossils** have led some biographers to describe him as the forefather of **geology** or one or more of its many branches.

After earning a medical degree in Italy, Agricola was appointed physician in the town of Joachimstahl in Bohemia (now Jachymov, Czechoslovakia). It was in this important mining center that he began some of his earliest research into mining and a lifelong love of geologic studies. When he later relocated to the mining center of Chemnitz (now in modern day Germany) he continued a remarkably systematic and meticulous research into the many facets of mining.

One of his earliest works, published in 1546, was *De Natura Fossileum* (On the nature of fossils). In this book, he summarized much of what was known by the ancient Greeks and Romans about fossils, **minerals**, and **gemstones**. In Agricola's time the meaning of the word fossil encompassed all three of these terms. It wasn't until early in the nineteenth century that the word was given its modern meaning. However, unlike other sixteenth century researchers, he did not accept ancient wisdom as fact. He ridiculed the mystical properties that many ancient scientists, physicians, and philosophers had assigned to fossils, minerals, and gemstones and derided Greek and Roman methods of classification. Instead of using alphabetical listings or groupings by supposed magical traits, Agricola developed a system that that relied on such properties as odor, taste, color, combustibility, shape, origin, brittleness, and cleavage. This classification system has endured for more than 450 years.

In another book, *De Ortu et Causis Subterraneum* (Of subterranean origins and sources), published the same year as *De Naturea Fossileum*, Agricola attempted to explain the existence of mountains, volcanoes, and earthquakes. Although the scientific equipment and knowledge of his time made some explanations impossible, Agricola recognized the power of **wind** and **water** as an erosive force, and associated the hot interior of Earth with volcanoes and earthquakes.

Despite the remarkable observations made by Agricola in *De Natura Fossileum, De Ortu et Causis Subteraneum*, and at least four other books, it is his seventh and final book, *De Re Metallica* (On the subject of **metals**), published in 1556 (one year after his death) that many geologists consider to be his finest work.

De Re Metallica was the culmination of years of careful and patient research in the two mining towns where Agricola served as a physician. Unlike many scientists before and during his time, he did not rely on hearsay or the work of others. According to Agricola, everything he wrote about he observed first hand or learned from reliable sources.

De Re Metallica was handsomely printed and illustrated with over 250 woodcuts on assaying (analyzing ores for their metallic content), pumps for removing water from mines, machinery for digging, and processes for smelting. The text included such topics as stratigraphy, minerals, finding and identifying ores, administrating mining operations, surveying, and even diseases related to mining.

Given the remarkable depth and scope of Georgius Agricola's research and publications it is not surprising that many modern geologists and historians consider his contributions essential to the early development of the science of geology.

AIR MASSES AND FRONTS

An air mass is an extensive body of air that has a relatively homogeneous **temperature** and moisture content over a significant altitude. Air masses typically cover areas of a few hundred, thousand, or million square kilometers. A front is the boundary at which two air masses of different temperature and moisture content meet. The role of air masses and fronts in the development of **weather** systems was first appreciated by the Norwegian father and son team of Vilhelm and Jacob Bjerknes in the 1920s. Today, these two phenomena are still studied intensively as predictors of future weather patterns.

Air masses form when a body of air comes to rest over an **area** large enough for it to take on the temperature and **humidity** of the land or **water** below it. Certain locations on the earth's surface possess the topographical characteristics that favor the development of air masses. The two most important of these characteristics are topographic regularity and atmospheric stability. Deserts, plains, and **oceans** typically cover very wide areas with relatively few topographical irregularities. In such regions, large masses of air can accumulate without being broken apart by mountains, land/water interfaces, and other features that would break up the air mass.

The absence of consistent **wind** movements also favors the development of an air mass. In regions where cyclonic or anticyclonic storms are common, air masses obviously cannot develop easily.

The system by which air masses are classified reflects the fact that certain locations on the planet possess the topographic and atmospheric conditions that favor air mass development. That system uses two letters to designate an air mass. One letter, written in upper case, indicates the approximate **lat-**

itude (and, therefore, temperature) of the region: A for arctic; P for polar; E for equatorial; T for tropical. The distinctions between arctic and polar on the one hand, and equatorial and tropical on the other are relatively modest. The first two terms (arctic and polar) refer to cold air masses, and the second two (equatorial and tropical) to warm air masses.

A second letter, written in lower case, indicates whether the air mass forms over land or sea and, hence, the relative amount of moisture in the mass. The two designations are c for continental (land) air mass and m for maritime (water) air mass.

The two letters are then combined to designate both temperature and humidity of an air mass. One source region of arctic air masses, for example, is the northern-most latitudes of Alaska, upper Canada, and Greenland. Thus, air masses developing in this source region are designated as cA (cold, land) air masses. Similarly, air masses developing over the **Gulf of Mexico**, a source region for maritime tropical air masses, are designated as mT (warm, water) air masses.

The movement of air masses across the earth's surface is an important component of the weather that develops in an area. For example, weather patterns in **North America** are largely dominated by the movement of about a half dozen air masses that travel across the continent on a regular basis. Two of these air masses are the cP and cA systems that originate in Alaska and central Canada and sweep down over the northern United States during the winter months. These air masses bring with them cold temperatures, strong winds, and heavy **precipitation**, such as the snowstorms commonly experienced in the **Great Lakes** states and New England. The name "Siberian Express" is sometimes used to describe some of the most severe storms originating from these cP and cA air masses.

From the south, mT air masses based in the Gulf of Mexico, the Caribbean, and western Atlantic Ocean move northward across the southern states, bringing hot, humid weather that is often accompanied by thunderstorms in the summer.

Weather along the western coast of North America is strongly influenced by mP air masses that flow across the region from the north Pacific Ocean. These masses actually originate as cP air over Siberia, but are modified to mP masses as they move over the broad expanse of the Pacific, where they often pick up moisture. When an mP mass strikes the west coast of North America, it releases its moisture in the form of showers and, in northern regions, snow.

The term front was suggested by the Bjerkneses because the collisions of two air masses reminded them of a battlefront during a military operation. That collision often results in warlike weather phenomena between the two air masses.

Fronts develop when two air masses with different temperatures and, usually, different moisture content come into contact with each other. When that happens, the two bodies of air act almost as if they are made of two different materials, such as oil and water. Imagine what happens, for example, when oil is dribbled into a **glass** of water. The oil seems to push the water out of its way and, in return, the water pushes back on the oil. A similar shoving match takes place between warm and cold air masses along a front. The exact nature of that shoving match depends on the relative temperature and moisture content of the two air masses and the relative movement of the two masses.

One possible situation is that in which a mass of cold air moving across the earth's surface comes into contact with a warm air mass. When that happens, the cold air mass may force its way under the warm air mass like a snow shovel wedging its way under a pile of snow. The cold air moves under the warm air because the former is denser. The boundary formed between these two air masses is a cold front.

Cold fronts are usually accompanied by a falling barometer and the development of large cumulonimbus **clouds** that bring rain showers and thunderstorms. During the warmer **seasons**, the clouds form as moisture-rich air inside the warm air mass, which is cooled as it rises; water subsequently condenses out as precipitation. Cold fronts are represented on weather maps by means of solid lines that contain solid triangles at regular distances along them. The direction in which the triangles point shows the direction in which the cold front is moving.

A situation opposite to the preceding is one in which a warm air mass approaches and then slides up and over a cold air mass. The boundary formed in this case is a warm front. As the warm air mass meets the cold air mass, it is cooled and some of the moisture held within it condenses to form clouds. In most cases, the first clouds to appear are high cirrus clouds, followed sometime later by stratus and nimbostratus clouds.

Warm fronts are designated on weather maps by means of solid lines to which are attached solid half circles. The direction in which the half circles point shows the direction in which the warm front is moving.

A more complex type of front is one in which a cold front overtakes a slower-moving warm front. When that happens, the cold air mass behind the cold front eventually catches up and comes into contact with the cold air mass underneath the warm front. The boundary between these two cold air masses is an occluded front. A distinction can be made depending on whether the approaching cold air mass is colder or warmer than the second air mass beneath the warm front. The former is called a cold-type occluded front, while the latter is a warm-type occluded front. Once again, the development of an occluded front is accompanied by the formation of clouds and, in most cases, by steady and moderate precipitation. An occluded front is represented on a weather map by means of a solid line that contains, alternatively, both triangles and half circles on the same side of the line.

In some instances, the collision of two air masses results in a stand-off. Neither mass is strong enough to displace the other, and essentially no movement occurs. The boundary between the air masses in this case is known as a stationary air mass and is designated on a weather map by a solid line with triangles and half circles on opposite sides of the line. Stationary fronts are often accompanied by fair, clear weather, although some light precipitation may occur.

See also Atmospheric circulation; Atmospheric composition and structure; Atmospheric pressure; Clouds and cloud types; Weather forecasting methods; Weather forecasting

AIR POLLUTION • *see* ATMOSPHERIC POLLUTION

ALKALINE EARTH METALS

On the **Periodic table**, Group 2 (IIA) consists of beryllium, magnesium, calcium, strontium, barium, and radium. This family of elements is known as the alkaline earth **metals**, or just the alkaline earths. Although early chemists gave the name "earths" to a group of naturally occurring substances that were unaffected by heat and insoluble in **water**, the alkaline earth metals are also usually found in the continental **crust**. In contrast, Group 1 compounds and ions tend to concentrate in the ocean.

Calcium carbonate is geologically evident as **limestone**, **marble**, coral, pearls, and chalk—all derived mainly from the shells of small marine animals. The **weathering** of calcium silicate rocks over millions of years converted the insoluble calcium silicate into soluble calcium salts, which were carried to the **oceans**. The dissolved calcium was used by marine organisms to form their shells. When the organisms died, the shells were deposited on the ocean floor where they were eventually compressed into sedimentary **rock**. Collisions of tectonic plates eventually allow this rock to rise above the ocean floor to become "land-based" limestone deposits.

Caverns throughout the world are formed by the action of atmospheric carbonic acid (water plus **carbon dioxide**) on limestone to form the more soluble calcium bicarbonate. When the solution of calcium bicarbonate reaches the open cavern and the water evaporates, **carbon** dioxide is released and calcium carbonate remains. The calcium carbonate is deposited as stalagmites if the drops hit the ground before evaporating, or as stalactites if the water evaporates while the drop hangs from above.

Other **minerals** of alkaline earth metals are beryllium **aluminum** silicate (beryl), calcium magnesium silicate (asbestos), potassium magnesium chloride (carnallite), calcium magnesium carbonate (**dolomite**), magnesium sulfate (epsomite), magnesium carbonate (magnesite), hydrogen magnesium silicate (talc), calcium fluoride (fluorspar), calcium fluorophosphate (fluorapatite), calcium sulfate (**gypsum**), strontium sulfate (celestite), strontium carbonate (strontianite), barium sulfate (barite), and barium carbonate (witherite). Radium compounds occur in pitchblende, which is primarily uranium oxide, because radium is a product of the radioactive disintegration of U-238. Most pitchblende in the United States is found in Colorado.

The alkaline earth metals, like the alkali metals, are too reactive to be found in nature except as their compounds; the two valence electrons completing an s-subshell are readily lost, and ions with +2 charges are formed. The alkaline earth metals all have a silver luster when their surfaces are freshly cut, but, except for beryllium, they tarnish rapidly. Like most metals, they are good conductors of **electricity**.

Only magnesium and calcium are abundant in Earth's crust. Magnesium is found in seawater and as the mineral carnallite, a combination of potassium chloride and magnesium chloride. Calcium carbonate exists as whole mountain ranges of chalk, limestone, and marble. Its most abundant mineral is **feldspar**, which accounts for two-thirds of the earth's crust. Beryllium is found as the mineral beryl, a beryllium aluminum silicate. With a chromium-ion impurity, beryl is known as emerald. If **iron** ions are present, the gemstone is blue-green and known as aquamarine.

Beryllium is lightweight and as strong as steel. It is hard enough to scratch **glass**. Beryllium is used for windows in x-ray apparatus and in other nuclear applications, allowing the rays to pass through with minimum absorption.

Because beryllium is rather brittle, it is often combined with other metals in alloys. Beryllium-copper alloys have unusually high tensile strength and resilience, which makes them ideal for use in springs and in the delicate parts of many instruments. The **alloy** does not spark, and so finds use in tools employed in fire-hazard areas. Because beryllium-nickel alloys resist **corrosion** by salt water, they are used in marine engine parts.

Magnesium, alone or in alloys, replaces aluminum in many construction applications because the supply of this metal from seawater is virtually unlimited. Magnesium is soft and can be machined, cast, and rolled. Magnesium-aluminum alloys (trade name Dowmetal) are often used in airplane construction.

Magnesium hydroxide is used as milk of magnesia for upset stomachs. Epsom salts are magnesium sulfate. Soapstone, a form of talc, is used for laboratory table tops and laundry tubs. Magnesium oxide is used for lining furnaces.

Slaked lime, or calcium hydroxide, is the principal ingredient in plaster and mortar, in which the calcium hydroxide is gradually converted to calcium carbonate by reaction with the carbon dioxide in the air. Slaked lime is an important flux in the reduction of iron in blast furnaces. It is also used as a mild germ-killing agent in buildings that house poultry and farm animals, in the manufacture of cement and sodium carbonate, for neutralizing acid **soil**, and in the manufacture of glass.

Calcium carbide, made by reacting calcium oxide with carbon in the form of coke, is the starting material for the production of acetylene. Calcium propionate is added to foods to inhibit mold growth. Calcium carbonate and calcium pyrophosphate are ingredients in toothpaste.

Plaster of Paris is $2CaSO_4 \cdot H_2O$, which forms $CaSO_4 \cdot 2H_2O$ (gypsum), as it sets. Gypsum is used to make wallboard, or sheet rock. Asbestos—no longer used as a building material in the United States because of concerns that exposure to asbestos fibers can cause cancer—is a naturally occurring mineral, a calcium magnesium silicate. Calcium and magnesium chlorides, byproducts of sodium chloride purification, are used in the de-icing of roads. Calcium chloride absorbs water from the air, so is used in the prevention of dust on roads, **coal**, and tennis courts and as a drying agent in the laboratory.

Florapatite, a calcium fluorophosphate, is an important starting material in the production of phosphoric acid, which, in turn, is used to manufacture fertilizers and detergents. The mines in Florida account for about one-third of the world's supply of this phosphate rock. Fluorspar, or calcium fluoride,

Steel is an alloy of iron and carbon. *© Wolfgang Kaeler/Corbis. Reproduced by permission.*

is used as a flux in the manufacture of steel. It is also used to make hydrofluoric acid, which is then used to make fluorocarbons such as Teflon.

Calcium is involved in the function of nerves and in blood coagulation. Muscle contraction is regulated by the entry or release of calcium ions by the cell. Calcium phosphate is a component of bones and teeth. Hydroxyapatite, calcium hydroxyphosphate, is the main component of tooth enamel. Cavities are formed when acids decompose this apatite coating. Adding fluoride to the diet converts the hydroxyapatite to a more acid-resistant coating, fluorapatite or calcium fluorophosphate. Magnesium is the metal ion in chlorophyll, the substance in plants that initiates the photosynthesis process in which water and carbon dioxide are converted to sugars. Calcium ions are needed in plants for cell division and cell walls. Calcium pectinate is essential in holding plant cells together. Calcium and magnesium ions are required by living systems, but the other Group 2 elements are generally toxic.

The word barium comes from the Greek *barys*, meaning heavy. Barium salts are opaque to x rays, and so a slurry of barium sulfate is ingested in order to outline the stomach and intestines in x-ray diagnosis of those organs. Although barium ions are poisonous, the very low solubility of barium sulfate keeps the concentration low enough to avoid damage.

Both barium and strontium oxides are used to coat the filaments of vacuum tubes, which are still used in some applications. Because these elements act to remove traces of **oxygen** and nitrogen, a single layer of barium or strontium atoms on a filament may increase the efficiency more than a hundred million times.

Radium is a source of radioactive rays traditionally used in cancer treatment, though other radioactive isotopes are now more commonly used. A radioactive isotope of strontium, strontium-90, is a component of nuclear fallout.

The alkaline earths and their compounds burn with distinctive colors. The green of barium, the red of strontium, and the bright white of magnesium are familiar in fireworks. Strontium is also used in arc lamps to produce a bright red light for highway flares.

See also Chemical bonds and physical properties; Chemical elements; Geochemistry; Stalactites and stalagmites

ALLOY

An alloy is a mixture of two or more elements, at least one of which is metallic, that itself has metallic properties (ductility, conductivity, etc.). Compounds that involve **metals** but do not have metallic properties are not alloys. Alloying occurs naturally; most raw gold, for example, is alloyed with silver, and natural nickel-iron alloys occur both in terrestrial rocks and as a common ingredient of meteorites. However, all alloys used for modern technological purposes are created industrially. This is necessary both because most raw metals exist as chemical compounds in rocks and because the balance of ingredients in a useful alloy must be precise.

In a given alloy, one metal is usually present in higher concentration than any other element; this is termed the parent metal or solvent of the alloy. Most alloys are solid at room **temperature**, and are assumed to be in the solid state when their properties are specified. Three common alloys are steel (parent metal **iron**, main additive **carbon**), bronze (parent metal copper, main additive tin), and brass (parent metal copper, main additive zinc).

The nature of the mixing in an alloy depends on the chemical properties of its ingredients. The atoms of the different elements in an alloy can be roughly classed as indifferent to each other, as attracting each other, or as repelling each other. If all atoms in an alloy are indifferent to each other, they mix randomly and produce an alloy that is uniform at all levels above the atomic. Such an alloy is termed a random solid solution. If the atoms of unlike elements in an alloy attract each other, some orderly pattern develops when the alloy cools from its molten to its solid state. Such a solid is termed a superlattice or ordered solid solution. For example, a half-copper, half-aluminum alloy is an ordered solid solution in which planes of **aluminum** atoms alternate with planes of copper atoms. However, if the unlike atoms in a substance are attracted by strong electrical forces, the result is not an ordered solid solution with metallic properties but a true chemical compound. Salt, for example (sodium chloride, NaCl), is considered an ionic compound, not an alloy of sodium.

If the unlike atoms in an alloy attract each other less than the like atoms, the elements tend to segregate into distinct crystal domains upon solidification. The alloy is then a mass of pure, microscopic **crystals** of its component elements and is termed a phase mixture.

See also Crystals and crystallography; Industrial minerals; Metals; Precious metals; Phase state changes

ALLUVIAL SYSTEM

An alluvial system is a landform produced when a stream or river, that is, some channelized flow (geologists call them all streams no matter what their scale) slows down and deposits sediment that was transported either as bedload or in suspension. The basic principle underlying alluvial deposits is that the more rapidly **water** is moving, the larger the particles it can hold in suspension and the farther it can transport those particles.

For example, suppose that a river is flowing across a mountainous region, eroding **rock**, **sand**, gravel, silt, and other materials from the stream bed. As long as the stream is flowing rapidly, a considerable quantity of materials such as these can be transported, either along the bottom or as particles suspended in the water column. But then imagine that the stream rushes out of the mountainous region and onto a valley floor. As the river slows down, suspended materials begin to be deposited. The larger bedload materials (for example, rocks and stones) accumulate first, and the lighter suspended materials (sand, silt, and **clay**) later. Any collection of materials deposited by a process such as this is known as *alluvium*. The conditions under which an alluvial system forms are found in both arid and humid climates, and in areas of both low slope (river deltas or swamps) and high slope (mountain streams).

Although the system mentioned above was in a mountainous setting, any river or stream is part of an alluvial system. Many stream systems consist of several common features including channels, heads, mouths, meanders, point bars and cut banks, **floodplains**, levees, oxbow **lakes**, and stream terraces.

The channel is the sloping trough-like depression down which water flows from the stream's origin, or head, to its destination, or mouth. All channels naturally curve, or meander. At the outside of a bend in a channel meander, the flow is concentrated and so **erosion** causes undercutting, and a cutbank forms. On the inside of the meander, flow decreases, so deposition occurs; a sand bar, or point bar, forms.

When a stream **floods**, several processes naturally follow. As the water flows out of its channel, it immediately begins to slow down because it spreads out over a large **area**, increasing the resistance to flow. Coarser sediments are therefore deposited very close to the channel. This forms a very gently sloping lump of alluvium that parallels the channel, known as a natural levee. As the natural levee builds up over thousands of years, it helps prevent flooding. That is why humans build man-made levees—to emulate natural levees. Finer sediments flow with the stream water out onto the flat area behind the levee, known as the floodplain.

During the same flood, if the water is especially high, or the channel is highly meandering, the flood may cut a new channel, connecting two closely positioned meanders, a neck, in what is called a neck cut-off. Once the neck is cut, the channel is much straighter, and the meander is abandoned to become a part of the floodplain. This abandoned meander then forms a lake known as an oxbow.

Another common feature of alluvial systems is the stream terrace. A stream terrace is simply an old floodplain that is now abandoned. Abandonment occurred when the erosive power of the stream increased and it began to rapidly downcut to a lower elevation. The stream did not have time to erode its old floodplain by meandering over it, so it was preserved. The abandoned floodplain, or stream terrace, can be seen well above the new stream channel elevation. Multiple terraces can sometimes be seen, resembling steps in a giant staircase.

When an alluvial system operates over a long period of time, perhaps millions of years, it works to flatten the surrounding landscape, and significantly decrease its average elevation. Areas that were originally mountainous can be worn down to rolling hills, and eventually produce extensive plains composed of alluvial sediment. The sediment is eroded from highlands that may be tens, hundreds, or perhaps thousands of miles from the coast, and the alluvium serves to bury existing coastal features beneath a blanket of sediment. During periods of lower sea level in the geologic past, coastal plains extended far out on the margins of the continents. Today, these alluvial sediments are hundreds of feet below sea level.

As a stream emerges from a mountain valley, its waters are dispersed over a relatively wide region of valley floor. Such is the case, for example, along the base of the Panamint Mountains that flank California's Death Valley. A stream flowing down a mountain side tends to deposit heavier materials near the foot of the mountain, somewhat lighter materials at a greater distance from the mountain, and the lightest materials at a still greater distance from the mountain.

Often, the flow of water ends within the deposited material itself. This material tends to be very porous, so water is more likely to soak into the ground than to flow across its surface. Thus, there is no preferred direction of deposition from side to side at the mouth of the stream, and as the alluvium accumulates it forms a cone-shaped pattern on the valley floor known as an alluvial fan.

The idealized model described above would suggest that an alluvial fan should have a gradually changing composition, with heavier materials such as rocks and small stones at the base of the mountain and lighter materials such as sand and silt at the base (toe) of the fan. In actual fact, alluvial fans seldom have this idealized structure. One reason for the more varied structure found in a fan is that stream flows change over time. During flows of low volume, lighter materials are deposited close to the mountain base on top of heavier materials deposited during earlier flows of high volume. During flows of high volume, heavier materials are once more deposited near the base of the mountain, now on top of lighter materials. A vertical cross-section of an alluvial fan is likely to be more heterogeneous, therefore, than would be suggested by an idealized depositional model.

Alluvial fans tend to have small slopes that may be no more than a foot every half a mile (a few tenths of a meter per kilometer). The exact slope of the fan depends on a number of factors. For example, streams that drain an extensive area, that have a large volume of water, or that carry suspended particles of smaller size are more likely to form fans with modest slopes than are streams with the opposite characteristics.

Under some circumstances, a river or stream may continue to flow across the top of an alluvial fan as well as soak into it. For example, the volume of water carried during floods may cause water to cut across an alluvial fan and empty onto the valley floor itself. Also, over time, sediments may become compacted within the fan, and it may become less and less porous. Then, the stream or river that feeds the fan may begin to cut a channel through the fan itself and to lay down a new fan at the base of the older fan. As the fans in a valley become more extensive, their lateral edges may begin to overlap each other. This feature is known as a bajada or piedmont alluvial plain.

In some regions, piedmont alluvial plains have become quite extensive. The city of Los Angeles, for example, is largely constructed on such a plain. Other extensive alluvial systems can be found in the Central Valley of California and along the base of the Andes Mountains in Paraguay, western Argentina, and eastern Bolivia.

Alluvial fans have certain characteristics that make them attractive for farming. In the first place, they generally have a somewhat reliable source of water (except in a **desert**): the stream or river by which they were formed. Also, they tend to be relatively smooth and level, making it easy for planting, cultivating, and harvesting.

Deltas are common alluvial features, and can be found at the mouths of most streams that flow into a lake or ocean. When **rivers** and streams flow into standing water, their velocity decreases rapidly. They then deposit their sediment load, forming a fan-shaped, sloping deposit very similar to an alluvial fan, but located in the water rather than on dry land. This is known as a **delta**. Deltas show a predictable pattern of decreasing sediment size as you proceed farther and farther from shore.

The Mississippi River Delta is the United States' best known delta. Other well-known deltas are the Nile Delta of northern **Africa** and the Amazon Delta of **South America**. When Aristotle observed the Nile Delta, he recognized it was shaped like the Greek letter, delta, hence the name. Most deltas clog their channels with sediment and so must eventually abandon them. If the river then flows to the sea along a significantly different path, the delta will be abandoned and a new delta lobe will form. This process, known as delta switching, helps build the coastline outward, forming new land for agriculture, as well as other uses.

ALPINE GLACIER • *see* GLACIERS

ALTOCUMULOUS CLOUD • *see* CLOUDS AND CLOUD TYPES

ALTOSTRATUS CLOUD • *see* CLOUDS AND CLOUD TYPES

ALUMINUM

Aluminum is the third most abundant element in the earth's **crust**, ranking only behind **oxygen** and **silicon**. It makes up about 9% of the earth's crust, making it the most abundant of all **metals**. The chemical symbol for aluminum, Al, is taken from the first two letters of the element's name.

Aluminum has an **atomic number** of 13 and an **atomic mass** of 26.98. Aluminum is a silver-like metal with a slightly bluish tint. It has a **melting** point of 1,220°F (660°C), a boiling point of about 4,440°F (2,450°C), and a density of 2.708 grams per cubic centimeter. Aluminum is both ductile and malleable.

Aluminum is a very good conductor of **electricity**, surpassed only by silver and copper in this regard. However, aluminum is much less expensive than either silver and copper. For that reason, engineers are currently trying to discover new ways in which aluminum can be used to replace silver and copper in electrical wires and equipment.

Aluminum occurs in nature as a compound, never as a pure metal. The primary commercial source for aluminum is the mineral bauxite, a complex compound consisting of aluminum, oxygen, and other elements. Bauxite is found in many parts of the world, including **Australia**, Brazil, Guinea, Jamaica, Russia, and the United States. In the United States, aluminum is produced in Montana, Oregon, Washington, Kentucky, North Carolina, South Carolina, and Tennessee.

Aluminum is extracted from bauxite in a two-step process. In the first step, aluminum oxide is separated from bauxite. Aluminum metal is produced from aluminum oxide.

At one time, The extraction of pure aluminum metal from aluminum oxide was very difficult. The initial process requires that aluminum oxide first be melted, then electrolyzed. This is difficult and expensive because aluminum oxide melts at only very high temperatures. An inexpensive method for carrying out this operation was discovered in 1886 by Charles Martin Hall, at the time, a student at Oberlin College in Ohio. Hall found that aluminum oxide melts at a much lower **temperature** if it is first mixed with a mineral known as cryolite. Passing electric current through a molten mixture of aluminum oxide and cryolite, produces aluminum metal.

At the time of Hall's discovery, aluminum was a very expensive metal. It sold for about $10 per pound—so rare and was displayed at the 1855 Paris Exposition next the French crown jewels. As a result of Hall's research, the price of aluminum dropped to less than $.40 per pound).

Aluminum was named for one of its most important compounds, alum, a compound of potassium, aluminum, sulfur, and oxygen. The chemical name for alum is potassium aluminum sulfate, $KAl(SO_4)_2$.

Alum has been widely used by humans for thousands of years. It was mined in ancient Greece and then sold to the Turks who used it to make a beautiful red dye known as Turkey red. Alum has also been long used as a mordant in dyeing. In addition, alum was used as an astringent to treat injuries.

Eventually, chemists began to realize that alum might contain a new element. The first person to actually produce aluminum from a mineral was the Danish chemist and physicist Hans Christian Oersted (1777-1851). Oersted was not very successful, however, in producing a very pure form of aluminum.

The first pure sample of aluminum metal was not made until 1827 when the German chemit Friedrich Wöhler heated a combination of aluminum chloride and potassium metal. Being more active, the potassium replaces the aluminum, leaving a combination of potassium chloride and aluminum metal.

Aluminum readily reacts with oxygen to form aluminum oxide: $4Al + 3O_2 \rightarrow 2Al_2O_3$. Aluminum oxide forms a thin, whitish coating on the aluminum metal that prevents the metal from reacting further with oxygen (i.e., **corrosion**).

The largest single use of aluminum alloys is in the transportation industry. Car and truck manufacturers use aluminum alloys because they are strong, but lightweight. Another important use of aluminum alloys is in the packaging industry. Aluminum foil, drink cans, paint tubes, and containers for home products are all made of aluminum alloys. Other uses of aluminum alloys include window and door frames, screens, roofing, siding, electrical wires and appliances, automobile engines, heating and cooling systems, kitchen utensils, garden furniture, and heavy machinery.

Aluminum is also made into a large variety of compounds with many industrial and practical uses. Aluminum ammonium sulfate, $Al(NH_4)(SO_4)_2$, is used as a mordant, in **water** purification and sewage treatment systems, in paper production and the tanning of leather, and as a food additive. Aluminum borate is used in the production of **glass** and ceramics.

One of the most widely used compounds is aluminum chloride ($AlCl_3$), employed in the manufacture of paints, antiperspirants, and synthetic rubber. It is also important in the process of converting crude **petroleum** into useful products, such as gasoline, diesel and heating oil, and kerosene.

See also Chemical elements; Minerals

ALVAREZ, LUIS (1911-1988)

American physicist

Luis Alvarez proposed a controversial theory involving the possibility of a massive collision of a meteorite with the earth 65 million years ago, an event that Alvarez believed may account for the disappearance of the dinosaurs. After a varied and illustrious career as a Nobel Prize-winning physicist, Alvarez shared his last major scientific achievement with his son Walter, who was then a professor of **geology** at The University of California at Berkeley. In 1980, the Alvarezes accidentally discovered a band of sedimentary **rock** in Italy that contained an unusually high level of the rare metal iridium. Dating techniques set the age of the layer at about 65 million years. The Alvarezes hypothesized that the iridium came from an asteroid that struck the earth, thereby sending huge volumes of smoke and dust (including the iridium) into the earth's atmosphere. They suggested that the cloud produced by the asteroid's impact covered the planet for an extended period of time, blocked out sunlight, and caused the widespread death of plant life on Earth's surface. The loss of plant life in turn, they theorized, brought about the extinction of dinosaurs, who fed on the plants. While the theory has found favor among many scientists and has been enhanced by additional findings, it is still the subject of scientific debate.

Luis Walter Alvarez was born in San Francisco, California. His father, Dr. Walter Clement Alvarez, was a medical researcher at the University of California at San Francisco and also maintained a private practice. Luis' mother was the former Harriet Skidmore Smythe. Alvarez's parents met while studying at the University of California at Berkeley.

Alvarez attended grammar school in San Francisco and enrolled in the city's Polytechnic High School, where he avidly studied science. When his father accepted a position at the prestigious Mayo Clinic, the family moved to Rochester, Minnesota. Alvarez reported in his autobiography *Alvarez: Adventures of a Physicist,* that his science classes at Rochester High School were "adequately taught [but] not very interesting." Dr. Alvarez noticed his son's growing interest in **physics** and hired one of the Mayo Clinic's machinists to give Luis private lessons on weekends. Alvarez enrolled at the University of Chicago in 1928 and planned to major in **chemistry**. He was especially interested in organic chemistry, but soon came to despise the mandatory chemistry laboratories. Alvarez "discovered" physics in his junior year and enrolled in a laboratory course, "Advanced Experimental Physics: Light" about which he later wrote in his autobiography: "It was love at first sight." He changed his major to physics and received his B.S. in 1932. Alvarez stayed at Chicago for his graduate work and his assigned advisor was Nobel Laureate Arthur Compton, whom Alvarez considered "the ideal graduate advisor for me" because he visited Alvarez's laboratory only once during his graduate career and "usually had no idea how I was spending my time."

Alvarez earned his bachelor's, master's, and doctoral degrees at the University of Chicago before joining the faculty at the University of California at Berkeley, where he remained until retiring in 1978. His doctoral dissertation concerned the diffraction of light, a topic considered relatively trivial, but his other graduate work proved to be more useful. In one series of experiments, for example, he and some colleagues discovered the "east-west effect" of cosmic rays, which explained that the number of cosmic rays reaching the earth's atmosphere differed depending on the direction from which they came. The east-west effect was evidence that cosmic rays consist of some kind of positively charged particles. A few days after passing his oral examinations for the Ph.D. degree, Alvarez married Geraldine Smithwick, a senior at the University of Chicago, with whom he later had two children. Less than a month after their wedding, the Alvarezes moved to Berkeley, California, where Luis became a research scientist with Nobel Prize-winning physicist Ernest Orlando Lawrence, and initiated an association with the University of California that was to continue for forty-two years.

Alvarez soon earned the title "prize wild idea man" from his colleagues because of his involvement in such a wide variety of research activities. Within his first year at Berkeley, he discovered the process of K-electron capture, in which some atomic nuclei decay by absorbing one of the electrons in its first orbital (part of the nuclear shell). Alvarez and a student, Jake Wiens, also developed a mercury vapor lamp consisting of the artificial isotope mercury–198. The U.S. Bureau of Standards adopted the wavelength of the light emitted by the lamp as an official standard of length. In his research with Nobel Prize-winning physicist Felix Bloch, Alvarez developed a method for producing a beam of slow moving neutrons, a method that was used to determine the magnetic moment of neutrons (the extent to which they affect a **magnetic field**). Just after the outbreak of World War II in **Europe**, Alvarez discovered tritium, a radioactive isotope (a variant **atom** containing a different number of protons) of hydrogen.

World War II interrupted Alvarez's work at Berkeley. In 1940, he began research for the military at Massachusetts Institute of Technology's (MIT's) radiation laboratory on radar (radio detecting and ranging) systems. Over the next three years, he was involved in the development of three new types of radar systems. The first made use of a very narrow radar beam to allow a ground-based controller to direct the "blind" landing of an airplane. The second system, code-named "Eagle," was a method for locating and bombing objects on the ground when a pilot could not see them. The third invention became known as the microwave early-warning system, a mechanism for collecting images of aircraft movement in overcast skies.

In 1943, Alvarez left MIT to join the Manhattan Project research team working in Los Alamos, New Mexico. His primary accomplishment with the team was developing the detonating device used for the first plutonium bomb. Alvarez flew in the B–29 bomber that observed the first test of an atomic device at Alamogordo, south of Los Alamos. Three weeks later, Alvarez was aboard another B–29 following the bomber "Enola Gay" as it dropped the first atomic bomb on Hiroshima, Japan. Like most scientists associated with the Manhattan Project, Alvarez was stunned and horrified by the destructiveness of the weapon he had helped to create. Nonetheless, he never expressed any doubts or hesitation about the decision to use the bombs, since they brought a swift end to the war. Alvarez felt strongly that the United States should continue its nuclear weapons development after the war and develop a fusion (hydrogen) bomb as soon as possible.

After the war, Alvarez returned to Berkeley where he had been promoted to full professor. Determining that the future of nuclear physics lay in high-energy research, he focused his research on powerful particle accelerators—devices that accelerate electrons and protons to high velocity. His first project was to design and construct a linear accelerator for use with protons. Although his machine was similar in some ways to the electron accelerators that had been available for many years, the proton machine posed a number of new problems. By 1947, however, Alvarez had solved those problems and his forty-foot-long proton accelerator began operation.

Over the next decade, the science of particle physics (the study of atomic components) developed rapidly at Berkeley. An important factor in that progress was the construction of the 184-inch synchrocyclotron at the university's radiation laboratory. The synchrocyclotron was a modified circular particle accelerator capable of achieving much greater velocities than any other type of accelerator. The science of particle physics involves two fundamental problems: creation of particles to be studied in some type of accelerator and detection and identification of those particles. After 1950, Alvarez's interests shifted from the first to the second of these problems, particle detection, because of a chance meeting in 1953 with University of Michigan physicist Donald Glaser. Glaser had recently invented the bubble chamber, a device that detects particles as they pass through a container of superheated fluid. As the particles move through the liquid, they form ions that act as nuclei on which the superheated material can begin to boil, thereby forming a track of tiny bubbles that shows the path taken by the particles. In talking with Glaser, Alvarez realized that the bubble chamber could be refined and improved to track the dozens of new particles then being produced in Berkeley's giant synchrocyclotron. Among these particles were some with very short lifetimes known as resonance states.

Improving Glaser's original bubble chamber involved a number of changes. First, Alvarez decided that liquid hydrogen would be a more sensitive material to use than the diethyl ether employed by Glaser. In addition, he realized that sophisticated equipment would be needed to respond to and record the resonance states that often lasted no more than a billionth of a second. The equipment he developed included relay systems that transmitted messages at high speeds and computer programs that could sort out significant from insignificant events and then analyze the former. Finally, Alvarez aimed at constructing larger and larger bubble chambers to record a greater number of events. Over a period of about five years, Alvarez's chambers grew from a simple one-inch **glass** tube to his most ambitious instrument, a 72-in (183 cm) chamber that was first put into use in 1959. With these devices, Alvarez eventually discovered dozens of new elementary particles, including the unusual resonance states.

The significance of Alvarez's work with bubble chambers was recognized in 1968 when he was awarded the Nobel Prize for physics. At the awards ceremony in Stockholm, the Swedish Academy of Science's Sten von Friesen stated that, because of his work with the bubble chamber, "entirely new possibilities for research into high-energy physics present themselves....Practically all the discoveries that have been made in this important field [of particle physics] have been possible only through the use of methods developed by Professor Alvarez." Alvarez attended the Nobel ceremonies with his second wife, Janet Landis, whom he married in 1958. The couple had two children.

Advancing years failed to reduce Alvarez's curiosity on a wide range of topics. In 1965 he was in charge of a **joint** Egyptian-American expedition whose goal was to search for hidden chambers in the pyramid of King Kefren at Giza. The team aimed high-energy muons (subatomic particles produced by cosmic rays) at the pyramid to look for regions of low density, which would indicate possible chambers. However, none were found. Alvarez's hobbies included flying, golf, music, and inventing. He made his last flight in his Cessna 310 in 1984, almost exactly 50 years after he first learned to fly. In 1963, he assisted the Warren Commission in the investigation of President John F. Kennedy's assassination. Among his inventions were a system for color television and an electronic indoor golf-training device developed for President Eisenhower. In all, he held 22 patents for his inventions. Alvarez died of cancer in Berkeley, at the age of 77.

AMORPHOUS

Solid substances fall into two general classes, crystalline and amorphous. Those whose atoms show long-range order, like the squares on a chessboard or the loops in a chain-link fence, are crystalline; those whose atoms are arranged in no particular, repeating pattern are amorphous. Naturally occurring amorphous solids are also termed mineraloids.

Amorphous solids are made of the same elements that produce crystalline solids, often mixed in the same ratios. For example, pure **silicon** dioxide (silica; SiO_2) occurs both in a crystalline form (e.g., **quartz**); and in an amorphous form (e.g., **glass**). The difference between the two forms is one of atomic-level organization. Given sufficient time, as when precipitating **atom** by atom from a hydrothermal solution or solidifying slowly from a pure melt, silicon and **oxygen** atoms assume an orderly, crystalline arrangement because it is a lower-energy state and therefore more stable, as a pencil lying on its side has less energy and is more stable than a pencil balanced on its eraser. However, if cooled suddenly, the silicon and oxygen atoms in, for example, molten silica have no time to line up in orderly crystalline ranks but are trapped in a random solid arrangement. Natural glasses (lechatelierites) are in fact produced in large quantities when silica-rich **lava** is quenched suddenly in air or, as during undersea eruptions, in **water**.

Although few amorphous solids beside glasses occur naturally, an amorphous form of virtually any substance can be manufactured by sufficiently rapid quenching of the liquid phase or by depositing atoms from the vapor phase directly onto a cool substrate. Vapor deposition is used to build up the amorphous silicon films found in all integrated electronic circuit chips.

Most natural amorphous solids are formed by fast quenching, but not all. The precious stone opal ($SiO_2 \cdot nH_2O$) is a mineraloid formed by the solidification of a colloidal solution (fine-particle mixture) of silica and water—in essence, opal is very firm silica jello. **Minerals** formed by solidification of colloids, like opal, are termed gel minerals. Limonite ($Fe_2O_3 \cdot nH_2O$) is another gel mineral.

A crystalline solid may be transformed into an amorphous solid by alpha-particle radiation emitted by uranium or thorium atoms contained in the crystal itself. Each alpha particle that passes through the crystal strikes a tiny but violent blow against its atomic structure, slightly scrambling the orderly ranks of atoms. A once-crystalline mineral whose crystal structure has been obliterated by alpha radiation is termed a metamict mineral.

See also Chemical bonds and physical properties; Crystals and crystallography

ANALEMMA

The earth's orbit around the **Sun** is not a perfect circle. It is an ellipse, albeit not a very flattened one, and this leads to a number of interesting observational effects. One of these is the analemma, the apparent path traced by the Sun in the sky when observed at the same time of day over the course of a year. The path resembles a lopsided figure eight (which is printed on some globes).

When measuring the Sun's position in the sky every day precisely at noon, over the course of a year the Sun appears to move higher in the sky as summer approaches and then move lower as winter approaches. This occurs because the tilt of Earth's axis causes the Sun's apparent celestial **latitude**, or *declination*, to change over the course of the year.

Mount St. Helens erupted explosively because its magma is andesitic, with increased amounts of trapped gas. ***AP/Wide World. Reproduced by permission.***

However, at some times of the year, the Sun will appear slightly farther west in the sky than it does at other times, as if it were somehow gaining time on a watch. This results from the ellipticity of Earth's orbit. According to Kepler's second law of motion, planets moving in an elliptical orbit will move faster when they are closer to the Sun than when they are farther away. Therefore, Earth's speed in its orbit is constantly changing, decelerating as it moves from perihelion (its closest point to the Sun) to aphelion (its farthest point from the Sun), and accelerating as it then "falls" inward toward perihelion again.

It would be nearly impossible for watchmakers to try to make a clock that kept actual solar time. The clock would have to tick at different rates each day to account for Earth's changing velocity about the Sun. Instead, watches keep what is called mean solar time, which is the average value of the advance of solar time over the course of the year. As a result, the Sun gets ahead of, and behind, mean solar time by up to 16 minutes at different times of the year. In other words, if one measured the position of the Sun at noon mean solar time at one time of year, the Sun might not reach that position until 12:16 P.M. at another time of year.

Now all the elements are in place to explain the analemma's figure eight configurations. The tilt of Earth's orbital axis causes the Sun to appear higher and lower in the sky at different times of year; this forms the vertical axis of the eight. The ellipticity of Earth's orbit causes the actual solar time to first get ahead of, and then fall behind, mean solar time. This makes the Sun appear to slide back and forth across the vertical axis of the eight, forming the rest of the figure.

The shape of the analemma depends upon a particular planet's orbital inclination and ellipticity. The Sun would appear to trace a unique analemma for any of the planets in the **solar system**; the analemmas thus formed are fat, thin, or even teardrop-shaped variants on the basic figure eight.

See also Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars

ANDESITE

Andesite is the most common volcanic **rock** after **basalt**. It is porphyritic, that is, consists of coarse **crystals** (phenocrysts) embedded in a granular or glassy matrix (groundmass). Having a silica content of 57%, it is in the intermediate category (52–66% silica) of the silicic–mafic scale. The large volcanic **mountain chains** of North and **South America**, including the Andes (for which andesite is named), are composed largely of andesite. Indeed, andesite is common in all the mountain-building zones that rim the Pacific Ocean. The transition from the oceanic **crust** of the main basin of the Pacific to the andesitic rocks around its perimeter is termed the andesite line. The crust on the deep-sea side of the andesite line is a product of **seafloor spreading**, and the andesitic mountains on the other side are a product of orogenic volcanism. The andesite line thus marks the geological border of the true Pacific basin.

The primary ingredient of most andesites is andesine, a **feldspar** of the **plagioclase** series. Smaller amounts of **quartz** or **minerals** rich in **iron** and magnesium such as **olivine**, pyroxene, biotite, or hornblende are also present. Andesites are ordered in three classes according to the identity of their nonfeldspar components: from most **silicic** to most **mafic**, these are (1) quartz-bearing andesites, (2) pyroxene andesites, and (3) biotite and hornblende andesites. All are intermediate in composition between diorite (an intrusive igneous rock consisting mostly of plagioclase feldspar) and **rhyolite**, a volcanic rock having the same composition as **granite** (i.e., feldspar plus quartz). In other words, andesites are higher in feldspar than rhyolite but lower in feldspar than diorites.

Andesite's character usually results from the **melting** and assimilation of rock fragments by **magma** rising to the surface. Rocks nearer the surface tend to be higher in **silicon**, because silicon is less dense than iron and magnesium, components that increase at greater depths. An andesite can thus be viewed very roughly as a basalt contaminated with excess silicon (and perhaps other ingredients). Indeed, many olivine-bearing andesites are so close to basalt in appearance that they can only be distinguished on the strength of chemical analysis.

Andesites high in quartz—dacites—are sometimes classed as a separate group.

See also Bowen's reaction series; Crust; Earth, interior structure; Minerals; Volcanic eruptions

ANGULAR UNCONFORMITIES • *see* UNCONFORMITIES

ANION • *see* CHEMICAL BONDS AND PHYSICAL PROPERTIES

ANNING, MARY (1799-1847)

English paleontologist

Mary Anning, a self-educated fossil hunter and collector, was eventually credited with the first discovery of the plesiosaur.

Anning was born in Lyme Regis in Dorset, England and remained single all her life. Lyme Regis is famous for its Jurassic ammonites and dinosaur remains. Her claim to fame was firmly established when she, along with her brother, found and extracted a complete ichthyosaur skeleton, subsequently sent to a London Museum. At the time she was only 12 years old. Anning also found a nearly complete skeleton of a plesiosaur in 1823, and made her third great discovery in 1828 of the anterior sheath and ink bag of Belemnospia. In 1929, she discovered the fossil fish Squaloraja, thought to be an ancestor of the shark and the ray. Her last major discovery in 1830 was the Plesiosaurus macrocephalus, named by Professor William Buckland.

Aning was born to a poor family and taught her initial trade by her father who was killed in an accident when she was 11 years old. However, over the next 35 years Anning knew and became known to most of the famous geologists of the time by collecting and running her fossil shop first with her mother, and then later on her own. Her knowledge of ammonites, dinosaur bones and other marine **fossils** found on the beach at Lyme Regis gave her fame, but not fortune. Towards the end of her life she was however, granted a government research grant in 1838 to help with her work. Because she was a woman, Anning was never allowed to present her work to the Geological Society of London.

Anning also never published any of her findings. Many of her discoveries are now displayed in museums although her name is rarely mentioned, as most the fossils carry the name of the donator, not the discoverer.

During her lifetime, in 1841 and 1844, Anning had two fossils named after her by **Louis Agassiz**, the Swiss exponent of the **Ice** Age theory. After her death, Anning was recognized by the very society that had failed to admit her during her lifetime, the Geological Society of London. She was an accomplished paleontologist, largely self-educated, and a highly intelligent woman even teaching herself French so that she could read Georges Cuvier's work in the original French. Today, scientists recognize Anning as an authority on British dinosaur anatomy.

See also Fossil record; Fossils and fossilization; Jurassic

ANNULAR ISLANDS • *see* GOYOTS AND ATOLLS

ANTARCTIC CIRCLE • *see* SOLAR ILLUMINATION: SEASONAL AND DIURNAL PATTERNS

ANTARCTIC OCEAN • *see* OCEANS AND SEAS

ANTARCTICA

Among the seven continents on planet Earth, Antarctica lies at the southernmost tip of the world. It is the coldest, driest, and windiest continent. **Ice** covers 98% of the land, and its 5,100,000 sq mi (13,209,000 sq km) occupy nearly one-tenth of Earth's land surface, or the same **area** as **Europe** and the United States combined. Despite its barren appearance, Antarctica and its surrounding waters and islands teem with life all their own, and the continent plays a significant role in the **climate** and health of the entire planet.

Seventy percent of the world's fresh **water** is frozen atop continental Antarctica. These icecaps reflect warmth from the **Sun** back into the atmosphere, preventing planet Earth from overheating. Huge **icebergs** break away from the stationary ice and flow north to mix with warm water from the equator, producing currents, **clouds**, and complex **weather** patterns. Creatures as small as microscopic phytoplankton and as large as whales live on and around the continent, including more than 40 species of birds. Thus, the continent provides habitats for vital links in the world's food chain.

Geologists believe that, millions of years ago, Antarctica was part of a larger continent called Gondwanaland, based on findings of similar **fossils**, rocks, and other geological features on all of the other southern continents. About 200 million years ago, Gondwanaland broke apart into the separate continents of Antarctica, **Africa**, **Australia**, **South America**, and India (which later collided with **Asia** to merge with that continent). Antarctica and these other continents drifted away from each other as a result of shifting of the plates of the earth's **crust**, a process called continental drift that continues today. The continent is currently centered roughly on the geographic South Pole, the point where all south latitudinal lines meet. It is the most isolated continent on Earth, 600 mi (1,000 km) from the southernmost tip of South America and more than 1,550 mi (2,494 km) away from Australia.

Antarctica is considered both an island and a continent. The land itself is divided into east and west parts by the Transantarctic Mountains. The larger side, to the east, is located mainly in the eastern longitudes. West Antarctica is actually a group of islands held together by permanent ice.

Almost all of Antarctica is under ice, in some areas by as much as 2 mi (3 km). The ice has an average thickness of about 6,600 ft (2,000 m), which is higher than many mountains in warmer countries. This grand accumulation of ice makes Antarctica the highest continent on Earth, with an average elevation of 7,500 ft (2,286 m).

While the ice is extremely high in elevation, the actual landmass of the continent is, in most places, well below sea level due to the weight of the ice. If all of this ice were to melt, global sea levels would rise by about 200 ft (65 m), flooding the world's major coastal ports and vast areas of low-lying land. Even if only one-tenth of Antarctica's ice were to slide into the sea, sea levels would rise by 20 ft (6 m), severely damaging the world's coastlines.

Under all the ice, the Antarctic continent is made up of mountains. The Transantarctic Mountains are the longest range on the continent, stretching 3,000 mi (4,828 km) from Ross Sea to Weddell Sea. Vinson Massif, at 16,859 ft (5,140 m), is the highest mountain peak. The few areas where mountains peek through the ice are called nunataks.

Among Antarctica's many mountain ranges lie three large, moon-like valleys—the Wright, Taylor, and Victoria Valleys—which are the largest continuous areas of ice-free land on the continent. Known as the "dry valleys," geologists estimate that it has not rained or snowed there for at least one million years. Any falling snow evaporates before it reaches the ground, because the air is so dry from the ceaseless winds and brutally cold temperatures. The dryness also means that decomposition is slow, and seal carcasses there have been found to be more than 1,000 years old. Each valley is 25 mi (40 km) long and 3 mi (5 km) wide and provides rare glimpses of the rocks that form the continent and the Transantarctic Mountains.

Around several parts of the continent, ice forms vast floating shelves. The largest, known as the Ross Ice Shelf, is about the same size as Texas. The shelves are fed by **glaciers** on the continent, so the resulting shelves and icebergs are made up of fresh frozen water. Antarctica hosts the largest glacier on Earth; the Lambert Glacier on the eastern half of the continent is 25 mi (40 km) wide and more than 248 mi (400 km) long.

Gigantic icebergs are a unique feature of Antarctic waters. They are created when huge chunks of ice separate from an ice shelf, a cliff, or glacier in a process known as calving. Icebergs can be amazingly huge; an iceberg measured in 1956 was 208 mi (335 km) long by 60 mi (97 km) wide (larger than some small countries) and was estimated to contain enough fresh water to supply London, England, for 700 years. Only 10–15% of an iceberg normally appears above the water's surface, which can create great dangers to ships traveling in Antarctic waters. As these icebergs break away from the continent, new ice is added to the continent by snowfall.

Icebergs generally flow northward and, if they do not become trapped in a bay or inlet, will reach the Antarctic Convergence, the point in the ocean where cold Antarctic waters meet warmer waters. At this point, ocean currents usually sweep the icebergs from west to east until they melt. An average iceberg will last several years before **melting**.

Three **oceans** surround Antarctica—the Atlantic, Pacific, and Indian Oceans. Some oceanographers refer to the parts of these oceans around Antarctica as the Southern Ocean. While the **saltwater** that makes up these oceans does not usually freeze, the air is so cold adjacent to the continent that even the salt and currents cannot keep the water from **freezing**. In the winter months, in fact, the ice covering the ocean waters may extend over an area almost as large as the continent. This ice forms a solid ring close to the continent and loose chunks at the northern stretches. In October (early spring) as temperatures and strong winds rise, the ice over the oceans breaks up, creating huge icebergs.

Because of the way the Earth tilts on its axis as it rotates around the Sun, both polar regions experience long winter nights and long summer days. At the South Pole itself, the sun shines around the clock during the six months of summer and virtually disappears during the cold winter months. The tilt also affects the angle at which the Sun's radiation hits the Earth. When it is directly overhead at the equator, it strikes the polar regions at more indirect angles. As a result, the Sun's radiation generates much less heat, even though the polar regions receive as much annual daylight as the rest of the world.

Even without the **wind chill**, the continent's temperatures can be almost incomprehensible to anyone who has not visited there. In winter, temperatures may fall to –100°F (–73°C). The world's record for lowest **temperature** was recorded on Antarctica in 1960, when it fell to –126.9°F (–88.3°C).

The coastal regions are generally warmer than the interior of the continent. The Antarctic Peninsula may get as warm as 50°F (10°C), although average coastal temperatures are generally around 32°F (0°C). During the dark winter months, temperatures drop drastically, however, and the warmest temperatures range from –4 to –22°F (–20 to –30°C). In the colder interior, winter temperatures range from –40 to –94°F (–40 to –70°C).

The strong winds that constantly travel over the continent as cold air races over the high ice caps and then flows down to the coastal regions, are called katabatic winds. Winds associated with Antarctica **blizzards** commonly gust to more than 120 mi (193 km) per hour and are among the strongest winds on Earth. Even at its calmest, the continent's winds can average 50–90 mi (80–145 km) per hour. Cyclones occur continually from west to east around the continent. Warm, moist ocean air strikes the cold, dry polar air and swirls its way toward the coast, usually losing its force well before it reaches land. These cyclones play a vital role in the exchange of heat and moisture between the tropical and the cold polar air.

Surprisingly, with all its ice and snow, Antarctica is the driest continent on Earth based on annual **precipitation** amounts. The constantly cold temperatures have allowed each year's annual snowfall to build up over the centuries without melting. Along the **polar ice** cap, annual snowfall is only 1–2 in (2.5–5 cm). More precipitation falls along the coast and in the coastal mountains, where it may snow 10–20 in (25–51 cm) per year.

Few creatures can survive Antarctica's brutal climate. Except for a few mites and midges, native animals do not exist on Antarctica's land. Life in the sea and along the coast of Antarctica and its islands, however, is often abundant. A wide variety of animals make the surrounding waters their home, from zooplankton to large birds and mammals. A few fish have developed their own form of antifreeze over the centuries to prevent ice **crystals** from forming in their bodies, while others have evolved into cold-blooded species to survive the cold.

Because the emperor penguin is one of the few species that lives on Antarctica year-round, researchers believe it could serve as an indicator to measure the health of the Antarctic ecosystem. The penguins travel long distances and hunt at various levels in the ocean, covering wide portions of the continent. At the same time, they are easily tracked because the emperor penguins return to their chicks and mates in predictable ways. Such indicators of the continent's health become more important as more humans travel to and explore Antarctica and as other global conditions are found to affect the southernmost part of the world.

A wide variety of research is continuing on Antarctica, primarily during the relatively warmer summer months from October to February when temperatures may reach a balmy 30–50°F (–1–10°C). The cold temperatures and high altitude of Antarctica allow astronomers to put their telescopes above the lower atmosphere, which lessens blurring. During the summer months, they can study the Sun around the clock, because it shines 24 hours a day. Antarctica is also the best place to study interactions between solar **wind** and Earth's **magnetic field**, temperature circulation in the oceans, unique animal life, **ozone** depletion, ice-zone ecosystems, and glacial history. Buried deep in Antarctica's ice lie clues to ancient climates, which may provide answers to whether the earth is due for **global warming** or the next ice age.

Scientists consider Antarctica to be a planetary bellwether, an early indicator of negative changes in the entire planet's health. For example, they have discovered that a hole is developing in the ozone layer over the continent, a protective layer of gas in the upper atmosphere that screens out the ultraviolet light that is harmful to all life on Earth. The ozone hole was first observed in 1980 during the spring and summer months, from September through November. Each year, greater destruction of the layer has been observed during these months, and the first four years of the 1990s have produced the greatest rates of depletion thus far. The hole was measured to be about the size of the continental United States in 1994, and it lasts for longer intervals each year. Scientists have identified various chemicals created and used by humans, such as chlorofluorocarbons (CFCs), as the cause of this destruction, and bans on uses of these chemicals have begun in some countries.

Researchers have also determined that a major climate change may have occurred in Antarctica in the 1980s and 1990s, based on recorded changes in ozone levels and an increase in cloudiness over the South Pole. This, coupled with a recorded weakening of the ozone shield over **North America** in 1991, has led scientists to conclude that the ozone layer is weakening around the entire planet.

Others are studying the ice cap on Antarctica to determine if, in fact, the earth's climate is warming due to the burning of fossil **fuels**. The global warming hypothesis is based on the atmospheric process known as the **greenhouse effect**, in which pollution prevents the heat energy of the earth from escaping into the outer atmosphere. Global warming could cause some of the ice cap to melt, flooding many cities and lowland areas. Because the polar regions are the engines that drive the world's weather system, this research is essential to identify the effect of human activity on these regions.

Most recently, a growing body of evidence is showing that the continent's ice has fluctuated dramatically in the past few million years, vanishing completely from the continent once and from its western third at least several times. These collapses in the ice structure might be triggered by climatic change, such as global warming, or by far less predictable factors, such as **volcanic eruptions** under the ice. While the east Antarctic ice sheet has remained relatively stable because it lies on a single tectonic plate, the western ice sheet is a jumble of small plates whose erratic behavior has been charted through **satellite** data.

See also Atmospheric pollution; Freshwater; Glacial landforms; Glaciation; Greenhouse gases and greenhouse effect; Ice ages; Ice heaving and wedging; Ozone layer and hole dynamics; Polar axis and tilt

ANTICLINE • *see* SYNCLINE AND ANTICLINE

APHANITIC

Crystalline rocks with mineral grains that cannot be distinguished from one another without magnification have an aphanitic igneous texture. **Igneous rocks** form by crystallization of **minerals** from liquid **magma** rising into the upper portion of Earth's **crust** from the lower crust and underlying mantle. Igneous **rock** texture indicates the rate of magmatic cooling. Crystallization takes place either slowly in deeply buried intrusions called plutons, or rapidly at the earth's surface where magma has been extruded as **lava** by volcanic activity. Igneous rocks are therefore classified as either intrusive (plutonic) or extrusive (volcanic). Slow, undisturbed cooling in a well-insulated pluton is conducive to orderly arrangement of atoms and molecules into large, well-formed **crystals**. Rapid cooling from a lava flow is not. Intrusive igneous rocks thus have coarse-grained, or phaneritic, textures with visible crystals, and extrusive igneous rocks have fine-grained, or aphanitic, texture. Volcanic **glass**, called **obsidian**, forms when lava is quenched and solidified so quickly that the silicate ions in the melt form no orderly atomic structure.

Texture indicates the rate at which an igneous rock cooled, but it has no relationship to the chemical or mineralogical composition of the rock. Aphanitic, extrusive, igneous rocks therefore have coarse-grained, intrusive counterparts with the same chemical and mineral composition. For example, the silica-rich extrusive rock, **rhyolite**, common in continental volcanic regions, is the fine-grained equivalent of intrusive **granite**. Both rock types are composed mainly of the silicate minerals **quartz** and orthoclase **feldspar**, but the crystals in the rhyolite are too small to see without a microscope. **Basalt**, the **iron** and magnesium-rich extrusive igneous rock that comprises the majority of the sea floor, has the same composition as the intrusive rock gabbro. The intermediate-composition extrusive igneous rock, **andesite**, is common in volcanic arcs above subduction zones, and its coarse-grained equivalent, diorite, is found in plutons along these same convergent plate tectonic margins.

See also Pluton and plutonic bodies

AQUIFER

An aquifer is a body of **sand** or porous **rock** capable of storing and producing significant quantities of **water**. An aquifer may be a layer of loose gravel or sand, a layer of porous **sandstone**, a **limestone** layer, or even an igneous or metamorphic body of rock. An aquifer may be only a few feet to hundreds of feet thick. Aquifers occur near the surface or buried thousands of feet below the surface. It may have an aerial extent of thousands of square miles or a few acres. The key requirements are that the layer or body has sufficient **porosity** to store the water, sufficient **permeability** to transmit the water, and be at least partly below the **water table**. The water table is the elevation of the top of the completely saturated (phreatic) zone. Above the water table is the vadose or **unsaturated zone** where the pore spaces are only partially saturated and contain a combination of air and water.

Porosity and permeability are important measures of producibility in aquifers. Porosity is the ratio of the volume of voids in a rock or **soil** to the total volume. Porosity determines the storage capacity of aquifers. In sand or **sedimentary rocks**, porosity is the space between grains and the volume of open space (per volume) in fractures. In dense rocks such as **granite**, porosity is contained largely within the crack and/or fracture system. Permeability is the capacity of a rock for transmitting a fluid, and is a measure of the relative ease with which a fluid can be produced from an aquifer.

A rock that yields large volumes of water at high rates must have many interconnected pore spaces or cracks. A dense, low porosity rock such as granite can be an adequate aquifer only if it contains an extensive enough system of connected fractures and cracks to be permeable. In the shallow subsurface, this is common because nearly all (indurate) rocks are fractured, often heavily. For that reason, caution should be exercised before assuming a low porosity rock will be an aquitard (impermeable body) and not an aquifer.

Fluid pressure, measured in pounds per square inch (psi), in an aquifer depends on whether it is unconfined or confined. An unconfined aquifer is one that is hydraulically open or connected to the surface. Examples would include sand bodies on or near the surface and more deeply buried layers of rock or sand connected to the surface by fractures and/or faults. The fluid pressure in unconfined aquifers is equivalent to what one would measure at a point in a standing body of water and would increase linearly (at a constant rate) with depth. The elevation of the top surface of an unconfined aquifer is free to fluctuate with rainfall.

A confined aquifer is one that is surrounded on all sides by an aquitard, a formation that does not transmit fluid. The pressure in a confined aquifer can be different from that of an unconfined aquifer at the same elevation. A body of sand surrounded on all sides by a soft, impermeable **clay** or shale serves as a typical example.

See also Hydrogeology; Saturated zone; Water table

ARCHEAN

The Archean is the period in the earth's history from about 3.8 to 2.5 billion years ago (Ga). The term was derived from the Latin word for first because the beginning of the Archean is defined as the age of the oldest rocks identified on Earth. As the study of these rocks continues and older rocks are discovered, some scientists now expand the Archean back to 4 billion years to include recently dated rocks. The Archean is part of the **Precambrian** Era, the entire time span between the formation of the earth 4.56 billion years ago and the beginning of the

Cambrian Era, 544 million years ago. The Archean is preceded by the Hadean Eon, a little used term for the period from which no rocks are preserved (4.56–3.8 Ga), and is followed by the Proterozoic (2.5–0.54 Ga).

Archean aged rocks are found mostly in the interior of continents. They provide evidence that Earth during the Archean was a very active geologic environment. Most of the rocks from the early Archean are highly regional metamorphic rocks. These granitic-gneiss versions of either sedimentary or igneous parent rocks suggest a high degree of lithospheric recycling. Later in the Archean, vast **lava** flows were erupted from undersea rift zones as pillow basalts. Subsequent **metamorphism** altered the basalts into greenstones. Some **sedimentary rocks** are preserved from the Archean and are largely coarse and poorly sorted sandstones and conglomerates. These observations suggest that the Archean Earth was very active tectonically with volcanic activity and movement along plate boundaries occurring at a much higher rate than today. The Archean mantle was much hotter than the modern Earth's interior, resulting in heavy mantle convection and crustal turbulence.

The active tectonics of the Archean produced numerous, relatively small continental landmasses that were very mobile as they floated on the turbulent mantle. Toward the end of the Archean, however, these minicontinents had begun to coalesce. By about 2.5 billion years ago when the Archean eon came to an end a more tectonically stable supercontinent had formed from the accreted landmasses. About 70% of modern continents are Archean in age and were derived from this single large landmass. This supercontinent had a much thicker **crust** than the earlier, smaller crusts and heat flow from the mantle had begun to subside. As a result volcanic and tectonic activity within and along the margins of the supercontinent, were reduced significantly by the start of the Proterozoic.

The first fossilized signs of life appeared in the Archean. Although life probably developed 3.8–3.6 billion years ago as non-photosynthetic bacteria, the oldest evidence of life on Earth are 3.5 Ga old stromatolite **fossils** from **Australia**. Stromatolites are finely layered, mound-shaped accumulations of mud trapped by growing mats of blue-green algae. Other early Archean fossils include 3.5 Ga microscopic filamentous structures resembling modern blue-green algae from Australia and cells apparently in various stages of division from South **Africa** in rocks that are 3.0 Ga old. The Archean atmosphere in which the primordial organisms developed was likely a reducing atmosphere of methane and ammonia. As the Archean progressed and photosynthetic organisms spread, the atmosphere became more **oxygen** rich.

See also Craton; Greenstone belt

ARCHEOLOGICAL MAPPING

An archeological map is used to relate the findings of an examination of an **area** (usually a dig or **remote sensing** analysis) to a particular set of geophysical coordinates (e.g., **latitude and longitude**). Archeological maps usually relate findings to three dimensions, including depth or altitude. Archeological maps help archeologists maintain accurate records that allows them to relate the results of their examination, to **GIS** maps and other specialized data processing and data depiction programs.

Before any excavation is begun at a site, the archeologist must prepare a survey map of the site. Site mapping may be as simple as a sketch of the site boundaries, or as complex as a topographic map complete with details about vegetation, artifacts, structures, and features on the site. By recording the presence of artifacts on the site, the site map may reveal information about the way the site was used, including patterns of occupational use. Contour maps may shed light on ways in which more recent environmental activity may have changed the original patterns of use. In cases where structural remains are visible at a site, the site map can provide a basis for planning excavations.

When staking out a site to be excavated, the archeologist typically lays out a square grid that will serve as a reference for recording data about the site. The tools required to construct the grid may be as simple as a compass, a measuring tape, stakes, and a ball of twine. After the grid has been laid out, the archeologist draws a representation of it on graph paper, being careful to note the presence of any physical landmarks such as trees, **rivers**, and large rocks. Once the excavation is underway, each artifact recovered is mapped into the square in the grid and layer in which it was found.

As artifacts are removed from each layer in the site, their exact positions are plotted on a map. At the end of the excavation, a record of the site will exist in the form of maps for each excavated layer at the site. Photographs are also taken of each layer for comparison with the maps.

To facilitate artifact recovery, deposited material at the site may be screened or sifted to make sure materials such as animal bones, snails, seeds, or chipping debris are not overlooked. When a screen is used, clumps of **soil** are thrown on it so that the dirt sifts through the screen, leaving any artifacts behind. In some cases, the deposit may be submerged in a container filled with plain or chemically treated **water**. When the water is agitated, light objects such as seeds, small bones, and charred plant material rise to the top of the container.

Prior to shipment to the laboratory for processing, artifacts are placed in a bag that is labeled with a code indicating the location and stratigraphic layer in which the artifacts were found. Relevant information about each artifact is recorded in the field notes for the site.

Many **mapping techniques** developed for use on land have also been adapted for underwater archeology. Grids can be laid out to assist in mapping and drawing the site, and to assist the divers who perform the excavation. In this case, however, the grids must be weighted to keep them from floating away, and all mapping, recording, and photographing must be done with special equipment designed for underwater use.

Most modern archeologists will attempt to place data taken from a site into archeological context by mapping the spatial and stratigraphic dimensions of the site.

Spatial dimensions include the distribution of artifacts, and other features in three dimensions. The level of detail given in the spatial description typically depends on the goals of the research project. One hundred years ago, finds were

Archeologists mapping a dig site. © *Layne Kennedy/Corbis. Reproduced by permission.*

recorded much less precisely than they are today; it might have been sufficient to map an object's location to within 25 sq yd (7 sq m). Today, the location of the same artifact might be recorded to the nearest centimeter. Modern archeologists still use maps to record spatial information about a site. Such information includes the spatial distribution of artifacts, features, and deposits, all of which are recorded on the map. Measuring tools range from simple tapes and plumb bobs to highly accurate and precise **surveying instruments** called laser theodolites.

The accuracy of a map is the degree to which a recorded measurement reflects the true value; the precision of the map reflects the consistency with which a measurement can be repeated. Although the archeologist strives for accuracy in representing the site by the map, the fact that much of what is recorded represents a subjective interpretation of what is present makes any map a simplification of reality. The levels of accuracy and precision that will be deemed acceptable for the project must be determined by the archeologists directing the investigation.

The second technique involved in recording the archeological context of a site is stratigraphic mapping. Any process that contributed to the formation of a site (e.g., dumping, flooding, digging, **erosion**, etc.) can be expected to have left some evidence of its activity in the stratification at the site. The sequential order these processes contribute to the formation of a site must be carefully evaluated in the course of an excavation. The archeologist records evidence of ordering in any deposits and interfaces found at the site for the purposes of establishing a relative chronology of the site and interpreting the site's history. In order to document the stratification at the site, the archeologist may draw or photograph vertical sections in the course of an excavation. Specific graphing techniques have been developed to aid archeologists in recording this information. Finally, the archeologist typically notes such details as soil color and texture, and the presence and size of any stones, often with the aid of reference charts to standardize the descriptions.

See also Bathometric mapping; Drainage calculations and engineering; Field methods in geology; Geologic map; GIS; Scientific data management in Earth Sciences; Topography and topographic maps

ARCMINUTES • *see* LATITUDE AND LONGITUDE

ARCSECONDS • *see* LATITUDE AND LONGITUDE

ARCTIC CIRCLE • *see* SOLAR ILLUMINATION: SEASONAL AND DIURNAL PATTERNS

ARCTIC OCEAN • *see* OCEANS AND SEAS

AREA

An accurate map requires precise geographic characterization of the land surface it represents. The two-dimensional extent of a region, or its area, is essential information for scientists whose studies include a geographic component. Land area measurement, however, is particularly critical for governments, industries, and individuals concerned with land management.

Human societies, beginning from the first agronomic civilizations of northern **Africa**, the Middle East, and China, and continuing with the modern geopolitical array of countries and cultures, have parceled their land between individuals, industries, cities, and nations. Geographers, from the ancient Egyptians and Greeks, to present-day remote **satellite remote sensing** and geographic information systems (**GIS**) specialists, have worked to devise methods of measuring land area, and of surveying land parcel boundaries.

Because the solid Earth has **topography**, and the two-dimensional plane of the Earth's curved surface is defined by three variables—longitude, **latitude**, and elevation—accurate calculation of land area is often quite complex. An area measurement of a topographic surface requires summation of the areas of measured rectangles small enough to capture areal variations introduced by variations in elevation. This summation can be accomplished by measuring and adding a sufficient number of small land areas, or by using integral calculus to compute the area of a three-dimensional surface. Both methods require precise measurement of geographic coordinates; the second also requires measurement of an elevation value at each survey point. In the Roman Empire, surveying (*limitatio*) and erection of measured survey markers (*terminatio*), preceded construction of geographic systems called *cadastres* that were composed of linear structures like roads and canals, and measured in *actus* (an *actus*) equaled 120 Roman feet, or 35.5 meters.

Cartographers during the fifteenth and sixteenth centuries, and European colonial surveyors in the seventeenth and eighteenth centuries, added surveyed elevations to their geographic systems by beginning surveys at sea level and calculating relative gain and loss of elevation at benchmarks. Today, satellite-aided global positioning (**GPS**), aeronautical and **space** remote sensing, and computer-assisted mapping of geographical information (GIS), have greatly enhanced the accuracy of land area measurements. However, most present-day land area surveys, including real estate appraisals and assessments of agricultural and forestry lands, measure land area by projecting the earth's three dimensional surface on to a flat surface. So, as it was in Rome, it is today; a hilly modern acre covers more area than a flat acre.

See also Archeological mapping; History of exploration II (Age of exploration); Physical geography; Surveying instruments

ARETES

Aretes are mountain (alpine) structures carved by glacial **ice**. To be more exact, they are carved by the continual action of cirques wearing away the tops of high elevation mountains. Consequently, it is necessary to understand the formation and erosional properties of cirques before the identification of an arete can occur.

Nivation, or the process of snow becoming compacted ice, begins at the mouth of small, high elevation valleys. As the ice continues to grow, its increased weight bears down on the surrounding **rock** and grinds the solid base into smaller debris. Cycles of daily melt and nighttime freeze produce frost-wedging, which in turn, loosens more surrounding rock. Meltwater carries the loosened debris down steep tributaries and away from growing deposits of ice. This ceaseless carving of the mountain forms a small bowl-like depression of ice that, over time, advances up the valley slope. At this point, the ice has identifiable properties and structure. Geologists call these structures cirques.

Cirques do not generally appear in isolation on higher elevation peaks. They are usually found in groups. In mountain ranges where ice sheets have not covered the surface and sheared the peaks, the action of encroaching cirques is free to carve distinctive patterns. As cirques grow and increase in number, they join or coalesce to form a continuous ridge of ice. When a ridge of cirques exists on the opposite side of the peak, the dual carving action meets to form a steep and serrated-looking crest of rock. This knifelike edge is called an arete. These imposing structures can be very treacherous and difficult to access. They are characteristically found in the Alps, Himalayas, and Andes mountains and give the ranges their distinct and rugged appearance. When three aretes meet on a particular peak, a distinctive type of tip emerges and is named a matterhorn peak. The tip is formed by the meeting of three aretes, which form a trapezoidal figure. The most famous matterhorn is found in the Alps where it is still being carved by cirques and defined by aretes.

See also Glacial landforms; Mountain chains

ARMSTRONG, NEIL (1930-)

American astronaut

Neil Armstrong was the first human to stand on the **Moon**. The former test pilot's lunar stroll on July 20, 1969 marked the pinnacle of the most ambitious engineering project ever undertaken. Afterwards, Armstrong pursued a career in aerospace teaching, research, and business.

Neil Alden Armstrong was fascinated by flying from the time of his first airplane ride when he was a six-year-old boy in Ohio. He was the son of Stephen Armstrong, an auditor who moved his family several times during Armstrong's childhood. When Neil was 13, Stephen and his wife, the former Viola Louise Engel, along with Neil and his younger brother and sister, settled in the town of Wapakoneta. Armstrong earned his pilot's license before his driver's license, and at sixteen was not only flying airplanes, but also experimenting with a **wind** tunnel he had built in his basement. He worked a variety of jobs to pay for his flying lessons and also played in a jazz band, pursuing the musical interest that remained a hobby throughout his life. Armstrong earned a Navy scholarship to Purdue University, which he entered in 1947. His schooling was interrupted when the Navy called him to active duty. Armstrong soon qualified as a Navy pilot, and he was flying combat missions in Korea at the age of 20. He flew 78 missions, earning three air medals.

After the Korean conflict, Armstrong left the navy and returned to Purdue. In 1955, he earned his bachelor's in aerospace engineering. In 1956, he married fellow Purdue student Janet Shearon. By then, Armstrong was a test pilot for the National Advisory Committee for Aeronautics, the forerunner of the National Aeronautics and Space Administration (NASA). At NACA's facility at Edwards Air Force Base in California, Armstrong flew a variety of aircraft under development. In 1960, Armstrong made his first of seven trips to the fringes of space in the X–15 rocket plane. The X–15, a sleek craft air-launched from a B–52 bomber and landed on Edwards's famous dry lake bed, gathered data about high-speed flight and atmospheric reentry that influenced many future designs, including the **space shuttle**.

When the astronaut program was first announced, Armstrong discounted it, believing that the winged X–15 design and not the *Mercury* capsule was the better approach to space. After John Glenn made the first U.S. orbital flight in

1962, Armstrong changed his mind and applied for NASA's astronaut corps. He was accepted into the second group of astronauts, becoming the first civilian to be chosen. In March, 1966, after serving as a backup for the *Gemini-Titan 5* mission, Armstrong made his first space flight as commander of *Gemini-Titan 8.* On this mission, Armstrong's capsule achieved the first docking between spacecraft in orbit. After docking the Gemini spacecraft to the Agena target vehicle, however, the combined vehicles began to tumble uncontrollably. Armstrong and co-astronaut David Scott disengaged the *Agena* and found the problem was a thruster on their capsule that was firing continuously. They had to shut down the flight control system to stop it, an action that forced the two astronauts to abort their flight.

Armstrong moved on to the moon-bound *Apollo* program. He was instrumental in adding a system that, in the event of a failure of the *Saturn 5* booster's guidance system, would allow the astronauts to fly the enormous vehicle manually. Armstrong was on the backup crew for *Apollo 8,* and in January, 1969, was selected to command *Apollo 11.* The crew included lunar module pilot Edwin "Buzz" Aldrin Jr. and command module pilot Michael Collins. Armstrong carried with him a piece of fabric and a fragment of a propeller from American aviators Wilbur and Orville Wrights' first airplane.

On July 20, 1969, the spider-shaped lunar module *Eagle* carried Armstrong and Aldrin toward the Sea of Tranquility. The pre-selected landing **area** turned out to be much rougher than thought, and Armstrong was forced to guide the *Eagle* over the terrain until he found a vacant site. The two men finally brought their craft to a soft landing with approximately thirty seconds' worth of fuel remaining. "The *Eagle* has landed," Armstrong reported. Almost seven hours later, he climbed down the ladder and took the epochal first step on the moon. Television viewers around the world watched as the astronaut in his bulky white suit uttered the words, "That's one small step for a man, one giant leap for mankind." (Viewers did not hear the word "a"; Armstrong later explained that his voice-operated microphone, which "can lose you a syllable," failed to transmit the word.)

Joined by Aldrin, Armstrong spent nearly three hours walking on the moon. The astronauts deployed experiments, gathered samples, and planted an American flag. They also left a mission patch and medals commemorating American and Russian space explorers who had died in the line of duty, along with a plaque reading, "Here men from the planet Earth first set foot upon the Moon. We came in peace for all mankind." Then the three men took their command module *Columbia* safely back to Earth. Armstrong and the other *Apollo 11* astronauts then traveled around the world for parades and speeches. The mission brought honors including the Presidential Medal of Freedom, the Harmon International Aviation Trophy, the Royal Geographic Society's Hubbard Gold Medal, and other accolades from a total of seventeen nations. Armstrong became a Fellow of the Society of Experimental Test Pilots, the American Astronautical Society, and the American Institute of Aeronautics and Astronautics.

Apollo 11 was Armstrong's final space mission. He moved to NASA's Office of Advanced Research and Technology, where he served as deputy associate administrator for aeronautics. One of his major priorities in this position was to further research into controlling high-performance aircraft by computer. In 1970, he earned his master's degree in aerospace engineering from the University of Southern California.

Neil Armstrong on the Moon.

A quiet man who values his privacy, Armstrong rejected most opportunities to profit from his fame. He left NASA in 1971, and moved his family back to Ohio to accept a position at the University of Cincinnati. There he spent seven years engaged in teaching and research as a professor of aerospace engineering. He took special interest in the application of space technology to challenges on Earth such as improving medical devices and providing data on the environment. In 1978, Armstrong was one of the first six recipients of the Congressional Space Medal of Honor, created to recognize astronauts whose "exceptionally meritorious efforts" had contributed to "the welfare of the Nation and mankind."

ARRHENIUS, SVANTE AUGUST (1859-1927)

Swedish chemist

Svante August Arrhenius was awarded the 1903 Nobel Prize in chemistry for his research on the theory of electrolytic dissociation, a theory that had won the lowest possible passing grade for his Ph.D. two decades earlier. Arrhenius's work with chemistry was often closely tied to the science of **physics**, so much so that the Nobel committee was not sure in which of the two fields to make the 1903 award. In fact, Arrhenius is regarded as one of the founders of physical chemistry—the field of science in which physical laws are used to explain chemical phenomena. In the last decades of his life Arrhenius became interested in theories of the **origin of life** on Earth, arguing that life had arrived on our planet by means of spores blown through **space** from other inhabited worlds. He was also one of the first scientists to study the heat-trapping ability of **carbon dioxide** in the atmosphere in a phenomenon now known as the **greenhouse effect**.

Arrhenius was born on February 19, 1859, in Vik (also known as Wik or Wijk), in the district of Kalmar, Sweden. His mother was the former Carolina Thunberg, and his father was Svante Gustaf Arrhenius, a land surveyor and overseer at the castle of Vik on Lake Mälaren, near Uppsala. Young Svante gave evidence of his intellectual brilliance at an early age. He taught himself to read by the age of three and learned to do arithmetic by watching his father keep books for the estate of which he was in charge. Arrhenius began school at the age of eight, when he entered the fifth-grade class at the Cathedral School in Uppsala. After graduating in 1876, Arrhenius enrolled at the University of Uppsala.

At Uppsala Arrhenius concentrated on mathematics, chemistry, and physics, and he passed the candidate's examination for the bachelor's degree in 1878. He then began a graduate program in physics at Uppsala, but left after three years of study. He was said to be dissatisfied with his physics advisor, Tobias Thalén, and felt no more enthusiasm for the only advisor available in chemistry, Per Theodor Cleve. As a result he obtained permission to do his doctoral research in absentia with the physicist Eric Edlund at the Physical Institute of the Swedish Academy of Sciences in Stockholm.

The topic Arrhenius selected for his dissertation was the electrical conductivity of solutions. In 1884 Arrhenius submitted his thesis on this topic. He hypothesized that when salts are added to **water** they break apart into charged particles now known as ions. What was then thought of as a molecule of sodium chloride, for example, would dissociate into a charged sodium **atom** (a sodium ion) and a charged chlorine atom (a chloride ion). The doctoral committee that heard Arrhenius's presentation in Uppsala was unimpressed by his ideas. Among the objections raised was the question of how electrically charged particles could exist in water. In the end the committee granted Arrhenius his Ph.D., but with a score so low that he did not qualify for a university teaching position.

Convinced that he was correct, Arrhenius had his thesis printed and sent it to a number of physical chemists on the continent, including Rudolf Clausius, Jacobus van't Hoff, and Wilhelm Ostwald. These men formed the nucleus of a group of researchers working on problems that overlapped chemistry and physics, developing a new discipline that would ultimately be known as physical chemistry. From this group Arrhenius received a much more encouraging response than he had received from his doctoral committee. In fact Ostwald came to Uppsala in August 1884 to meet Arrhenius and to offer him a job at Ostwald's Polytechnikum in Riga. Arrhenius was flattered by the offer and made plans to leave for Riga, but eventually declined for two reasons. First, his father was gravely ill (he died in 1885), and second, the University of Uppsala decided at the last moment to offer him a lectureship in physical chemistry.

Arrhenius remained at Uppsala only briefly, however, as he was offered a travel grant from the Swedish Academy of Sciences in 1886. The grant allowed him to spend the next two years visiting major scientific laboratories in **Europe**, working with Ostwald in Riga, Friedrich Kohlrausch in Würzburg, Ludwig Boltzmann in Graz, and van't Hoff in Amsterdam. After his return to Sweden, Arrhenius rejected an offer from the University of Giessen, Germany, in 1891 in order to take a teaching job at the Technical University in Stockholm. Four years later he was promoted to professor of physics there. In 1903, during his tenure at the Technical University, Arrhenius was awarded the Nobel Prize in chemistry for his work on the dissociation of electrolytes.

Arrhenius remained at the Technical University until 1905 when, declining an offer from the University of Berlin, he became director of the physical chemistry division of the Nobel Institute of the Swedish Academy of Sciences in Stockholm. He continued his association with the Nobel Institute until his death in Stockholm on October 2, 1927.

Although he will be remembered best for his work on dissociation, Arrhenius was a man of diverse interests. In the first decade of the twentieth century, for example, he became especially interested in the application of physical and chemical laws to biological phenomena. In 1908 Arrhenius published a book entitled *Worlds in the Making* in which he theorized about the transmission of life forms from planet to planet in the universe by means of spores.

Arrhenius's name has also surfaced in recent years because of the work he did in the late 1890s on the greenhouse effect. He theorized that **carbon** dioxide in the atmosphere has the ability to trap heat radiated from the Earth's surface, causing a warming of the atmosphere. Changes over time in the concentration of carbon dioxide in the atmosphere would then, he suggested, explain major climatic variations such as the glacial periods. In its broadest outlines, the Arrhenius theory sounds similar to current speculations about **climate** changes resulting from **global warming**.

See also Atmospheric chemistry; Greenhouse gases and greenhouse effect

ARTESIAN

Artesian refers to a condition in which **groundwater** flows from a well without the aid of a pump or other artificial means. One can speak of artesian wells, artesian aquifers, or artesian **water**. Artesian conditions arise when the energy per unit weight possessed by groundwater is great enough to force the water from a deeply buried **aquifer** to the ground surface in the event that the aquifer is tapped by a well. Artesian wells were used by ancient Egyptians, and the word artesian comes from the French province of Artois, where the first European artesian well was constructed in 1126.

The energy per unit weight of groundwater is known as hydraulic head and consists of two main components, elevation head and pressure head. Elevation head is the potential energy per unit weight due to the elevation of the groundwater, whereas pressure head is the energy per unit weight arising as water flows downward and is compressed by the weight of the overlying water. Flowing groundwater also possesses kinetic energy proportional to the square of its velocity, but groundwater generally moves so slowly that its velocity head is virtually nonexistent. Hydraulic head has units of length and is measured relative to some reference elevation, typically sea level; in practical terms, it is defined as the elevation to which groundwater will rise in a specially constructed well known as a piezometer. Thus, the hydraulic head of artesian groundwater must be equal to or greater than the elevation of the ground surface to which it is flowing.

Artesian aquifers are confined, meaning that they are sandwiched between lower **permeability** aquitards. Artesian water enters confined aquifers at high elevations and flows downward towards areas of lower hydraulic head. Although elevation head decreases as groundwater flows downward within an aquifer, pressure head increases because the aquifer is confined and energy must be conserved. Artesian groundwater, therefore, has nearly the same hydraulic head deep underground as it did when it entered the confined aquifer at a higher elevation. When a well is drilled into the artesian aquifer, the hydraulic head of the groundwater will be great enough that the water will rise to nearly the elevation at which it entered the aquifer.

See also Hydrogeology; Hydrologic cycle; Hydrostatic pressure

ASIA

Asia is the world's largest continent, encompassing an **area** of 17,177,000 sq mi (44,500,000 sq km), 29.8% of the world's land area. The Himalaya Mountains, which are the highest and youngest mountain range in the world, stretch across the continent from Afghanistan to Burma. The highest of the Himalayan peaks, Mount Everest, reaches an altitude of 29,028 ft (8,848 m). There are many famous deserts in Asia, including the Gobi **Desert**, the Thar Desert, and Ar-Rub'al-Khali ("the Empty Quarter"). The continent has a wide range of climatic zones, from the tropical jungles of the south to the Arctic wastelands of the north in Siberia.

The continent of Asia encompasses such an enormous area and contains so many countries and islands that its exact borders remain unclear. In the broadest sense, it includes central and eastern Russia, the countries of the Arabian Peninsula, the Far Eastern countries, the Indian subcontinent, and numerous island chains. It is convenient to divide this huge region into five categories: the Middle East, South Asia, Central Asia, the Far East, and Southeast Asia.

Rice is a staple food for much of Asia. © ***Roger Ressmeyer/Corbis. Reproduced by permission.***

The Middle Eastern countries lie on the Arabian Peninsula, southwest of Russia and northeast of **Africa**, separated from the African continent by the Red Sea and from **Europe** in the northwest by the Mediterranean Sea. This area stretches from Turkey in the northwest to Yemen in the south, which is bordered by the Arabian Sea. In general, the **climate** is extremely dry, and much of the area is still a desert wilderness. **Precipitation** is low, so the fertile regions of the Middle East lie around the **rivers** or in valleys that drain the mountains. Much of the coastal areas are arid, and the vegetation is mostly desert scrub.

Saudi Arabia is the largest of the Middle Eastern countries. In the west it is bordered by the Red Sea, which lies between Saudi Arabia and the African continent. The Hijaz Mountains run parallel to this coast in the northwest, rising sharply from the sea to elevations ranging from 3,000 to 9,000 ft (910 to 2,740 m). In the south is another mountainous region called the Asir, stretching along the coast for about 230 mi (370 km) and inland about 180–200 mi (290–320 km). Between the two ranges lies a narrow coastal plain called the Tihamat ash-Sham. East of the Hijaz Mountains are two great plateaus called the Najd, which slopes gradually downward over a range of about 3,000 ft (910 m) from west to east, and the Hasa, which is only about 800 ft (240 m) above sea level. Between these two plateaus is a desert region called the Dahna.

About one third of Saudi Arabia is estimated to be desert. The largest of these is the Ar-Rub'al-Khali, which lies in the south and covers an area of about 250,000 sq mi (647,500 sq km). In the north is another desert, called the An-Nafud. The climate in Saudi Arabia is generally very dry; there are no **lakes** and only seasonally flowing rivers. Saudi Arabia, like most of the Middle Eastern countries, has large oil reserves; also found here are rich gold and silver mines which are thought to date from the time of King Solomon.

Israel contains three main regions. Along the Mediterranean Sea lies a coastal plain. Inland is a hilly area that includes the hills of Galilee in the north and Samaria and Judea in the center. In the south of Israel lies the Negev Desert, which covers about half of Israel's land area. The two bodies of **water** in Israel are the Sea of Galilee and the Dead Sea. The latter, which takes its name from its heavy salinity, lies 1,290 ft (393 m) below sea level, and is the lowest point on the earth's landmasses. It is also a great resource for potassium chloride, magnesium bromide, and many other salts. Jordan borders on Israel in the east near the Dead Sea. To the east of the Jordan River, which feeds the Dead Sea, is a plateau region. The low hills gradually slope downward to a large desert, which occupies most of the eastern part of the country.

Lebanon borders Israel in the north and is divided up by its steep mountain ranges. These have been carved by **erosion** into intricate clefts and valleys, lending the landscape an unusual rugged beauty. On the western border, which lies along the Mediterranean Sea, is the Mount Lebanon area. These mountains rise from sea level to a height of 6,600–9,800 ft (2,000–3,000 m) in less than 25 mi (40 km). On the eastern border is the Anti-Lebanon mountain range, which separates Lebanon from Syria. Between the mountains lies Bekaa Valley, Lebanon's main fertile region.

Syria has three major mountain ranges. In the southwest, the Anti-Lebanon mountain range separates the country geographically from Lebanon. In the southeast is the Jabal Ad-Duruz range, and in the northwest, running parallel to the Mediterranean coast, are the Ansariyah Mountains. Between these and the sea is a thin stretch of coastal plains. The most fertile area is in the central part of the country east of the Anti-Lebanon and Ansariyah mountains; the east and northeastern part of Syria is made up of steppe and desert region.

Turkey, at the extreme north of the Arabian Peninsula, borders on the Aegean, the Mediterranean, and the Black **Seas**. Much of the country is cut up by mountain ranges, and the highest peak, called Mount Ararat, reaches an altitude of 16,854 ft (5,137 m). In the northwest is the Sea of Marmara, which connects the Black Sea with the Aegean Sea. Most of this area, called Turkish Thrace, is fertile and has a temperate climate. In the south, along the Mediterranean, there are two fertile plains called the Adana and the Antalya, which are separated by the Taurus Mountains.

The two largest lakes in Turkey are called Lake Van, which is close to the border with Iraq, and Lake Tuz, which lies in the center of the country. Lake Tuz has such a high level of salinity that it is actually used as a source of salt. Turkey is a country of seismic activity, and earthquakes are frequent.

Most of the Far Eastern countries are rugged and mountainous, but rainfall is more plentiful than in the Middle East, so there are many forested regions. Volcanic activity and **plate tectonics** have formed many island chains in this region of the world, and nearly all the countries on the coast include some of these among their territories.

China, with a land area of 3,646,448 sq mi (9,444,292 sq km), is an enormous territory. The northeastern part of the country is an area of mountains and rich forestland, and its mineral resources include **iron**, **coal**, gold, oil, **lead**, copper, and magnesium. In the north, most of the land is made up of fertile plains. It is here that the Yellow (Huang) River is found, which has been called "China's sorrow" because of its great flooding. The northwest of China is a region of mountains and highlands, including the cold and arid steppes of Inner Mongolia. It is here that the Gobi Desert, the fifth largest desert in the world, is found. The Gobi was named by the Mongolians, and its name means "waterless place." It encompasses an area of 500,000 sq mi (1,295,000 sq km), and averages 2–4 in (5–10 cm) of rainfall a year. In contrast, central China is a region of fertile land and temperate climate. Many rivers, including the great Chang (Yangtze) River, flow through this region, and there are several **freshwater** lakes. The largest of these, and the largest in China, is called the Poyang Hu. In the south of China the climate becomes tropical, and the land is very fertile; the Pearl (Zhu or Chu) River **delta**, which lies in this region, has some of the richest agricultural land in China. In the southwestern region, the land becomes mountainous in parts, and coal, iron, phosphorous, manganese, **aluminum**, tin, **natural gas**, copper, and gold are all found here. In the west, before the line of the Himalayas which divides China from India, lies Tibet, which is about twice as large as Texas and makes up about a quarter of China's land area. This is a high plateau region, and the climate is cold and arid. A little to the north and east of Tibet lies a region of mountains and grasslands where the Yangtze and Yellow Rivers arise.

Japan consists of a group of four large islands, called Honshu, Hokkaido, Kyushu, and Shikoku, and more than 3,000 smaller islands. It is a country of intense volcanic activity, with more than 60 active volcanoes, and frequent earthquakes. The terrain is rugged and mountainous, with lowlands making up only about 29% of the country. The highest of the mountain peaks is an extinct **volcano** found on Honshu called Mount Fuji. It reaches an altitude of 12,388 ft (3,776 m). Although the climate is generally mild, tropical cyclones usually strike in the fall, and can cause severe damage.

Central Asia includes Mongolia and central and eastern Russia. This part of Asia is mostly cold and inhospitable. While only 5% of the country is mountainous, Mongolia has an average elevation of 5,184 ft (1,580 m). Most of the country consists of plateaus. The **temperature** variation is extreme, ranging from –40 to 104°F (–40 to 40°C). The Gobi Desert takes up about 17% of Mongolia's land mass, and an additional 28% is desert steppe. The remainder of the country is forest steppe and rolling plains.

North of China and Mongolia lies Russian Siberia. This region is almost half as large as the African continent, and is usually divided into the eastern and western regions. About the top third of Siberia lies within the Arctic Circle, and the climate is very harsh. The most extreme temperatures occur in eastern Siberia, where it falls as low as –94°F (–70°C), and there are only 100 days a year when it climbs above 50°F (10°C). Most of the region along the east coast is mountainous, but in the west lies the vast West Siberian Plain.

The most important lake in this area, and one of the most important lakes in the world, is called Lake Baikal. Its surface area is about the size of Belgium, but it is a mile deep and contains about a fifth of the world's fresh water supply. The diversity of aquatic life found here is unparalleled; it is the only habitat of 600 kinds of plants and 1,200 kinds of animals, making it the home of two-thirds of the freshwater species on Earth.

Southeast Asia includes a number of island chains as well as the countries east of India and south of China on the mainland. The area is quite tropical, and tends to be very humid. Much of the mountainous regions are extremely rugged and inaccessible; they are taken up by forest and jungle and have been left largely untouched; as a result, they provide habitat for much unusual wildlife.

Thailand, which is a country almost twice the size of Colorado, has a hot and humid tropical climate. In the north, northeast, west, and southeast are highlands that surround a central lowland plain. This plain is drained by the river Chao Phraya, and is rich and fertile land. The highlands are mostly covered with **forests**, which include tropical rainforests, deciduous forests, and coniferous pine forests. Thailand also has two coastal regions; the largest borders on the Gulf of Thailand in the east and southeast, and on the west is the shore of the Andaman Sea.

South of the mainland countries lie the island chains of Malaysia, Indonesia, and the Philippines. The latter two are both sites of much volcanic activity; Indonesia is estimated to have 100 active volcanoes. These islands, in particular Malaysia, are extremely fertile and have large regions of tropical rain forests with an enormous diversity in the native plant and wildlife.

South Asia includes three main regions: the Himalayan mountains, the Ganges Plains, and the Indian Peninsula.

The Himalayas stretch about 1,860 mi (3,000 km) across Asia, from Afghanistan to Burma, and range from 150 to 210 mi (250 to 350 km) wide. They are the highest mountains in the world, and are still being pushed upward at a rate of about 2.3 in (6 cm) a year. This great mountain range originated when the Indian subcontinent collided with Asia, which occurred due to the subduction of the Indian plate beneath the Asian continent. The Himalayas are the youngest mountains in the world, which accounts in part for their great height. At present they are still growing as India continues to push into the Asian continent at the rate of about 2.3 in (6 cm) annually. The Indian subcontinent is believed to have penetrated at least 1,240 mi (2,000 km) into Asia thus far. The range begins in Afghanistan, which is a land of harsh climate and rugged environment.

Bordered by China, several former Russian breakaway republics, Pakistan, and Iran, Afghanistan is completely landlocked. High, barren mountains separate the northern plains of Turan from the southwestern desert region, which covers most of Afghanistan's land area. This desert is subject to violent sandstorms during the winter months. The mountains of Afghanistan, which include a spur of the Himalayas called the Hindu Kush, reach an elevation of more than 20,000 ft (6,100 m), and some are snow-covered year-round and contain **glaciers**. The rivers of the country flow outward from the mountain range in the center of the country; the largest of these are the Kabul, the Helmand, the Hari Rud, and the Kunduz. Except for the Kabul, all of these dry up soon after flowing onto the dry plains.

To the east of Afghanistan and separated from it by the Hindu Kush, lies Pakistan. In the north of the country are the mountain ranges of the Himalayas and the Karakoram, the highest mountains in the world. Most of the peaks are over 15,000 ft (4,580 m) and almost 70 are higher than 22,000 ft (6,700 m). By comparison, the highest mountain in the United States, Mount McKinley in Alaska, is only 20,321 ft (6,194 m). Not surprisingly, many of the mountains in this range are covered with glaciers.

In the west of the country, bordering on Afghanistan, is the Baluchistan Plateau, which reaches an altitude of about 3,000–4,000 ft (900–1,200 m). Further south, the mountains disappear, replaced by a stony and sandy desert. The major rivers of Pakistan are the Kabul, the Jhelum, the Chenab, the Ravi, and the Sutlej; all of these drain into the Indus River, which flows into the Arabian Sea in the south of Pakistan.

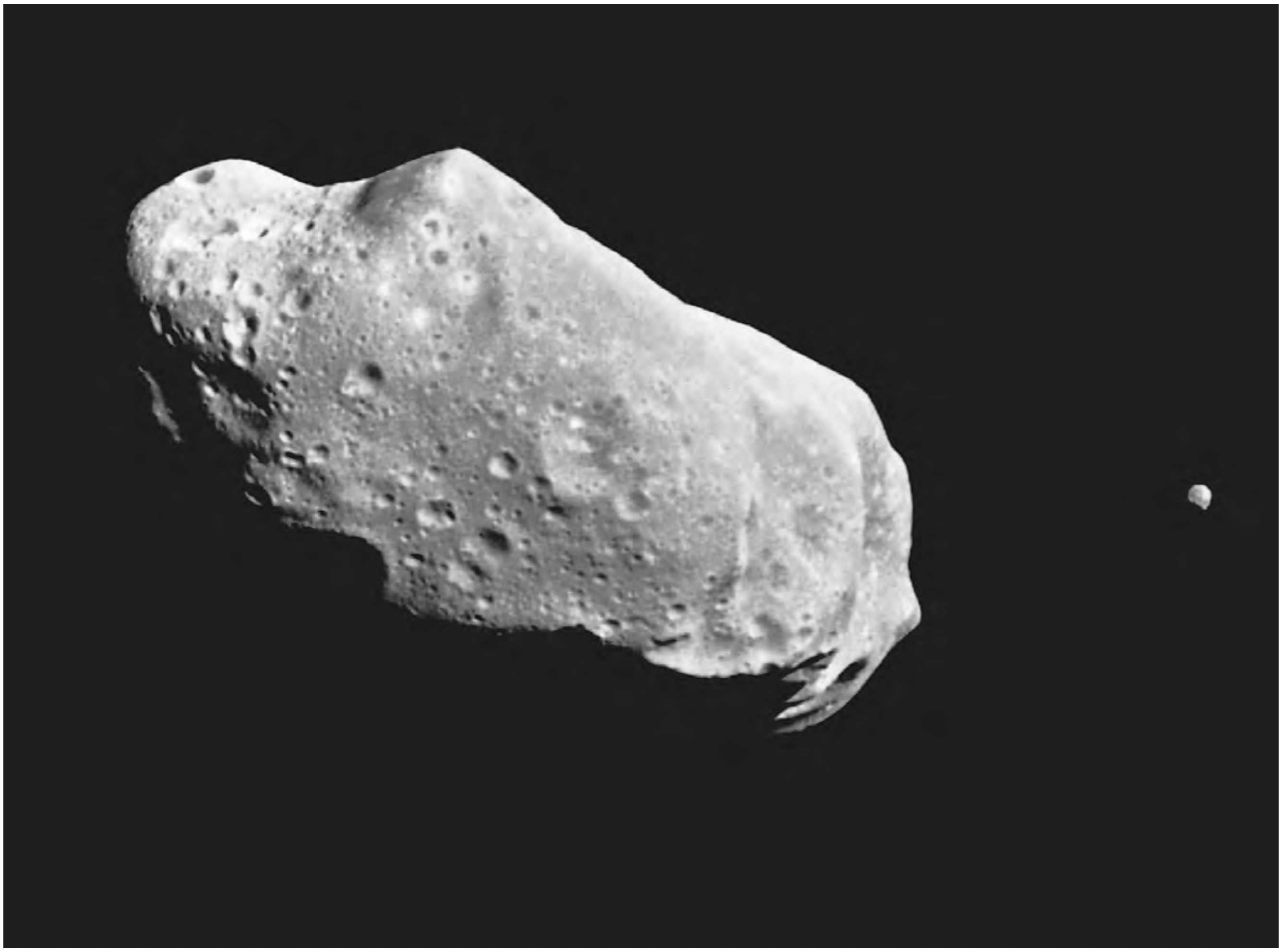
Also found in the Himalaya Mountains are Nepal and the kingdom of Bhutan. Both of these countries border on the fertile Ganges Plains, so that in the south they are densely forested with tropical jungles; but most of both territories consist of high mountains. It is in Nepal that the highest peak in the world, called Mount Everest, is found; it is 29,028 ft (8,848 m) high.

South of the Himalaya Mountains, India is divided into two major regions. In the north are the Ganges Plains, which stretch from the Indus to the Ganges River delta. This part of India is almost completely flat and immensely fertile; it is thought to have alluvium reaching a depth of 9,842 ft (3,000 m). It is fed by the snow and **ice** from the high peaks, and streams and rivers from the mountains have carved up the northern edge of the plains into rough gullies and crevices. Bangladesh, a country to the north and east of India, lies within the Ganges Plains. The Ganges and the Brahmaputra flow into Bangladesh from India, and they are fed by many tributaries, so the country is one of the most well-watered and fertile regions of Asia. However, it is also close to sea level, and plagued by frequent flooding.

ASTEROID BELT • *see* SOLAR SYSTEM

ASTEROIDS

Asteroids are rocky material left over from the formation of the **solar system** that orbit the **Sun**, but are too small to be



Asteroid 243 Ida and its moon, photograph. ***Corbis Corporation. Reproduced by permission.***

viewed as planets. Most asteroids are composed of stone, **iron**, nickel, or a combination of the three ingredients, and resemble terrestrial rocks in appearance. Asteroids can range in size from pebble-sized rocks up to almost 1,000 km in diameter. Asteroids whose orbits will eventually cause them to collide with Earth are known as **meteoroids**. When the heat and friction of entering Earth's atmosphere at high velocity causes the meteoroid to burn brightly in its path across the sky, it is known as a meteor. Particles or chunks of the meteor that survive the atmospheric entry and fall to Earth are meteorites. Asteroids are classified according to their composition, size, or location. Although Near-Earth Asteroids (NEAs) have been observed in Earth's orbit, the vast majority of asteroids, including the largest asteroid Ceres, are located in the Main Asteroid Belt between Mars and Jupiter.

The astronomer **Johannes Kepler** (1571–1630) was the first to postulate the existence of a hidden planet between Mars and Jupiter, a theory long considered by future astronomers, and in the region now known to contain the solar system's Main Asteroid Belt. In 1766, Johannes Titius (1729–1796), a professor of mathematics and **physics** in Germany, developed a formula for calculating planetary distances that also suggested a planet belonged between Mars and Jupiter. When the planet Uranus was discovered in 1781, it fit into the formula, causing many scientists to be even more certain that the hidden planet existed. One astronomer, Franz Xaver, proposed the formation of a society of astronomers that would be responsible for looking in assigned areas of the sky for the mystery planet.

Father Giuseppe Piazzi (1746–1826), was involved in such a search at this time. During the night of New Year's Eve, 1800, he saw a small star in Taurus. Because he couldn't find it listed in star catalogues, he observed it over several nights. Piazzi discovered that the body moved relative to the fixed stars, so it had to be an object that belonged to the solar system. Discovering the largest asteroid in the solar system, Piazzi gave this object the name of Ceres, the patron goddess of Sicily. Piazzi was unable, however, to calculate Ceres's orbit from so few observations. A German mathematician, Carl Friedrich Gauss, became intrigued with the problem and invented a new method for orbit calculations. Using his technique, the small object was rediscovered in the winter of

1801–02. That same winter, another German, Heinrich Olbers (1758–1840), found a second planetoid: Pallas.

This second discovery sparked a debate: were these two objects remnants of some planet's catastrophe, or did they always exist in their present form? It is now known that all the asteroids together would produce an object much smaller than our **moon**, so it is unlikely they were ever in one piece. Scientists generally agree that asteroids are leftovers from the formation of the solar system out of the solar nebula.

In 1804 and 1807, two more asteroids were found. The third was called Juno, and the fourth was dubbed Vesta. These were the only planetoids found until the mid-1800s, when telescopic equipment and techniques improved. From 1854 until 1870, five new asteroids were discovered every year. The all-time champion asteroid hunter in the days before photography was Johann Palisa (1848–1932) who found 53 by 1900, and added many more before his death.

In 1891, the German astronomer Maximilian Wolf (1863–1932) began using photographic techniques to search for asteroids. He had his **telescope** set up to follow the apparent motion of the stars, so that any other object like an asteroid would produce a short line in a photographic image rather than a dot like the stars. There had been about 300 asteroids found up until his time, but the use of photography opened the floodgates. Wolf alone discovered 228 asteroids. Astronomers now estimate that roughly 100,000 asteroids exist that are bright enough to appear on photographs taken from Earth.

Asteroids are not uniformly distributed in **space**. The huge planet Jupiter has captured some planetoids, called Trojan asteroids, which are found in two clusters ahead and behind the giant planet. They gather at these two points because of the gravitational forces of the Sun and Jupiter. In addition to these, there are other asteroids that have odd orbits that bring them into the inner regions of the solar system. A few have come close to the earth: in 1937, Hermes swept within 600,000 miles of the earth (only twice the distance from the Earth to the Moon); in 1989, another asteroid came within 500,000 miles of our planet. There is evidence that occasionally an asteroid, or a piece of one, has collided with the earth; one of the best-preserved impact craters can be seen in Arizona.

Because they are remnants of the beginnings of our solar system, asteroids can provide astronomers with valuable information about the conditions under which the solar system was formed.

See also Barringer meteor crater; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Comets; Hubble Space Telescope; Meteoroids and meteorites; Solar system

ASTHENOSPHERE

The asthenosphere is the layer of Earth that lies at a depth 60–150 mi (100–250 km) beneath Earth's surface. It was first named in 1914 by the British geologist J. Barrell, who divided Earth's overall structure into three major sections: the **lithosphere**, or outer layer of rock-like material; the asthenosphere; and the centrosphere, or central part of the planet. The asthenosphere gets its name from the Greek word for weak, asthenis, because of the relatively fragile nature of the materials of which it is made. It lies in the upper portion of Earth's structure traditionally known as the mantle.

Geologists are somewhat limited as to the methods by which they can collect information about Earth's interior. For example, they may be able to study rocky material ejected from volcanoes and **lava** flows for hints about properties of the interior regions. But generally speaking, the single most dependable source of such information is the way in which seismic waves are transmitted through Earth's interior. These waves can be produced naturally as the result of earth movements, or they can be generated synthetically by means of explosions, air guns, or other techniques.

Seismic studies have shown that a type of wave known as S-waves slow down significantly as they reach a depth of about 62 mi (100 km) beneath Earth's surface. Then, at a depth of about 155 mi (250 km), their velocity increases once more. Geologists have taken these changes in wave velocity as indications of the boundaries for the region now known as the asthenosphere.

The material of which the asthenosphere is composed can be described as plastic-like, with much less rigidity than the lithosphere above it. This property is caused by the interaction of **temperature** and pressure on asthenospheric materials. Any **rock** will melt if its temperature is raised to a high enough temperature. However, the **melting** point of any rock is also a function of the pressure exerted on the rock. In general, as the pressure is increased on a material, its melting point increases.

The temperature of the materials that make up the asthenosphere tend to be just below their melting point. This gives them a plastic-like quality that can be compared to **glass**. As the temperature of the material increases or as the pressure exerted on the material increases, the material tends to deform and flow. If the pressure on the material is sharply reduced, so will be its melting point, and the material may begin to melt quickly. The fragile melting point pressure balance in the asthenosphere is reflected in the estimate made by some geologists that up to 10% of the asthenospheric material may actually be molten. The rest is so close to being molten that relatively modest changes in pressure or temperature may cause further melting.

In addition to loss of pressure on the asthenosphere, another factor that can bring about melting is an increase in temperature. The asthenosphere is heated by contact with hot materials that make up the **mesosphere** beneath it. Obviously, the temperature of the mesosphere is not constant. It is hotter in some places than in others. In those regions where the mesosphere is warmer than average, the extra heat may actually increase the extent to which asthenospheric materials are heated and a more extensive melting may occur.

The asthenosphere is now thought to play a critical role in the movement of plates across the face of Earth's surface. According to plate tectonic theory, the lithosphere consists of a relatively small number of very large slabs of rocky material. These plates tend to be about 60 mi (100 km) thick and many thousands of miles wide. They are thought to be very rigid themselves but capable of flowing back and forth on top of the asthenosphere. The collision of plates with each other, their lateral sliding past each other, and their separation from each other are thought to be responsible for major geologic features and events such as volcanoes, lava flows, mountain building, and deep-sea rifts.

In order for plate tectonic theory to seem sensible, some mechanism must be available for permitting the flow of plates. That mechanism is the semi-fluid character of the asthenosphere itself. Some observers have described the asthenosphere as the lubricating oil that permits the movement of plates in the lithosphere.

Geologists have now developed sophisticated theories to explain the changes that take place in the asthenosphere when plates begin to thin or to diverge from or converge toward each other. For example, suppose that a region of weakness has developed in the lithosphere. In that case, the pressure exerted on the asthenosphere beneath it is reduced, melting begins to occur, and asthenospheric materials begin to flow upward. If the lithosphere has not actually broken, those asthenospheric materials cool as they approach Earth's surface and eventually become part of the lithosphere itself.

On the other hand, suppose that a break in the lithosphere has actually occurred. In that case, the asthenospheric materials may escape through that break and flow outward before they have cooled. Depending on the temperature and pressure in the region, that outflow of material (**magma**) may occur rather violently, as in a **volcano**, or more moderately, as in a lava flow.

Pressure on the asthenosphere may also be reduced in zones of divergence, where two plates are separating from each other. Again, this reduction in pressure may allow asthenospheric materials in the asthenosphere to begin melting and to flow upward. If the two overlying plates have actually separated, asthenospheric material may flow through the separation and form a new section of lithosphere.

In zones of convergence, where two plates are flowing toward each other, asthenospheric materials may also be exposed to reduced pressure and begin to flow upward. In this case, the lighter of the colliding plates slides upward and over the heavier of the plates, which dives down into the asthenosphere. This process is called subduction. Since the lithospheric material is more rigid than the material in the asthenosphere, the latter is pushed outward and upward. During this movement of plates, pressure on the asthenosphere is reduced, melting occurs, and molten materials flow upward to Earth's surface. In any one of the examples cited here, the asthenosphere supplies new material to replace lithospheric materials that have been displaced by some other tectonic or geologic mechanism.

See also Continental drift theory; Continental shelf; Crust; Earth, interior structure; Plate tectonics

ASTROLABE

The astrolabe is an ancient astronomical instrument, dating back more than 2,000 years, used to observe the positions of the stars. With modifications it has also been used for timekeeping, navigation, and surveying.

Astrolabes depict the visual reference points of stars on the night sky as a function of time. As such, an observer can also set the time to predict the visible star pattern expected. The most common type of astrolabe, the planispheric astrolabe, consists of a star map (the rete) engraved on a round sheet of metal. With regard to the rete, only the angular relationship of the stars needs to be accurate to ensure proper functioning of the astrolabe. A metal ring is moved across the map to represent the position of the local horizon. An outer ring is adjusted to allow for the apparent **rotation** of the stars around the North Star, using prominent stars as reference points.

Astrolabes were forerunners of mechanical clocks, and looked somewhat like watches. With a set of tables, the observer could determine the day and hour for a fixed location by the position of the stars. With the addition of a sighting-rule, called an alidade, an astrolabe could be used as a surveying instrument. The rule could be moved across a scale to measure elevation. Navigational astrolabes marked celestial altitudes (the altitude in degrees above the horizon).

Although there is evidence to support the assertion that ancient Greek culture had astrolabes, it is certain that the Arabs perfected and made regular use of the astrolabe. With the clear **desert** sky at their constant disposal, the Arab people excelled in **astronomy** and used the stars to navigate across the **seas** of **sand**. Regular use of astrolabes continued into the 1800s. The newer prismatic astrolabe continues to be used for precision surveying.

Modern versions of stellar charts and bowls with adjustable time and date markings on sliding rings are based upon earlier astrolabe construction and design principles.

See also Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; History of exploration I (Ancient and classical); History of exploration II (Age of exploration)

ASTRONOMY

Astronomy, the oldest of all the sciences, seeks to describe the structure, movements, and processes of celestial bodies.

Some ancient ruins provide evidence that the most remote ancestors observed and attempted to understand the workings of the Cosmos. Although not always fully understood, these ancient ruins demonstrate that early man attempted to mark the progression of the **seasons** as related to the changing positions of the **Sun**, stars, planets, and **Moon** on the celestial sphere. Archaeologists speculate that such observation made more reliable the determination of times for planting and harvest in developing agrarian communities and cultures.

The regularity of the heavens also profoundly affected the development of indigenous religious beliefs and cultural practices. For example, according to Aristotle (384-322 B.C.), Earth occupied the center of the Cosmos, and the Sun and planets orbited Earth in perfectly circular orbits at an unvarying rate of speed. The word astronomy is a Greek term for star arrangement. Although heliocentric (Sun centered) theories were also advanced among ancient Greek and Roman scientists, the embodiment of the geocentric theory conformed to prevailing religious beliefs and, in the form of the Ptolemaic model subsequently embraced by the growing Christian church, dominated Western thought until the rise of empirical science and the use of the **telescope** during the Scientific Revolution of the sixteenth and seventeenth centuries.

In the East, Chinese astronomers carefully charted the night sky, noting the appearance of "guest stars" (**comets**, novae, etc.). As early as 240 B.C., the records of Chinese astronomers record the passage of a "guest star" known now as Comet Halley, and in A.D. 1054, the records indicate that one star became bright enough to be seen in daylight. Archaeoastronmers argue that this transient brightness was a supernova explosion, the remnants of which now constitute the Crab Nebula. The appearance of the supernova was also recorded by the Anasazi Indians of the American Southwest.

Observations were not limited to spectacular celestial events. After decades of patient observation, the Mayan peoples of Central America were able to accurately predict the movements of the Sun, Moon, and stars. This civilization also devised a calendar that accurately predicted the length of a year, to what would now be measured to be within six seconds.

Early in the sixteenth century, Polish astronomer **Nicolas Copernicus** (1473–1543) reasserted the heliocentric theory abandoned by the Greeks and Romans. Although sparking a revolution in astronomy, Copernicus' system was deeply flawed by an insistence on circular orbits. Danish astronomer Tycho Brahe's (1546–1601) precise observations of the celestial movements allowed German astronomer and mathematician **Johannes Kepler** (1571–1630) to formulate his laws of planetary motion that correctly described the elliptical orbits of the planets.

Italian astronomer and physicist **Galileo Galilei** (1564–1642) was the first scientist to utilize a newly invented telescope to make recorded observations of celestial objects. In a prolific career, Galileo's discoveries, including phases of Venus and moons orbiting Jupiter, dealt a death blow to geocentric theory.

In the seventeenth century, English physicist and mathematician Sir Isaac Newton's (1642–1727) development of the laws of motion and gravitation marked the beginning of Newtonian **physics** and modern astrophysics. In addition to developing calculus, Newton made tremendous advances in the understanding of light and optics critical to the development of astronomy. Newton's seminal 1687 work, *Philosophiae Naturalis Principia Mathematica* (Mathematical principles of natural philosophy) dominated the Western intellectual landscape for more than two centuries and proved the impetus for the advancement of celestial dynamics.

Hubble image of the Eagle Nebula, "the Pillars of Creation." ***U.S. National Aeronautics and Space Administration (NASA).***

Theories surrounding celestial mechanics during the eighteenth century were profoundly shaped by important contributions by French mathematician Joseph-Louis Lagrange (1736–1813), French mathematician Pierre Simon de Laplace (1749–1827), and Swiss mathematician Leonhard Euler (1707–1783) that explained small discrepancies between Newton's predicted and the observed orbits of the planets. These explanations contributed to the concept of a clockwork-like mechanistic universe that operated according to knowable physical laws.

Just as primitive astronomy influenced early religious concepts, during the eighteenth century, advancements in astronomy caused significant changes in Western scientific and theological concepts based upon an unchanging, immutable God who ruled a static universe. During the course of the eighteenth century, there developed a growing scientific disregard for understanding based upon divine revelation and a growing acceptance of an understanding of Nature based upon the development and application of scientific laws. Whether God intervened to operate the mechanisms of the universe through miracles or signs (such as comets) became a topic of lively philosophical and theological debate. Concepts of the divine became increasingly identified with the assumed eternity or infinity of the Cosmos. Theologians argued that the assumed immutability of a static universe, a concept shaken by the discoveries of Copernicus, Kepler, Galileo, and Newton, offered proof of the existence of God. The clockwork universe viewed as confirmation of the existence of God of infinite power who was the "prime mover" or creator of the universe. For many scientists and astronomers, however, the revelations of a mechanistic universe left no place for the influence of the Divine, and they discarded their religious views. These philosophical shifts sent sweeping changes across the political and social landscape.

In contrast to the theological viewpoint, astronomers increasingly sought to explain “miracles” in terms of natural phenomena. Accordingly, by the nineteenth century, the appearances of comets were no longer viewed as direct signs from God but rather a natural, explainable and predictable result of a deterministic universe. Explanations for catastrophic events (e.g., comet impacts, extinctions, etc.) increasingly came to be viewed as the inevitable results of time and statistical probability.

The need for greater accuracy and precision in astronomical measurements, particularly those used in navigation, spurred development of improved telescopes and pendulum driven clocks that greatly increased the pace of astronomical discovery. In 1781, improved mathematical techniques, combined with technological improvements, along with the proper application of Newtonian laws, allowed English astronomer William Herschel to discover the planet Uranus.

Until the twentieth century, astronomy essentially remained concerned with the accurate description of the movements of planets and stars. Developments in electromagnetic theories of light and the formulation of quantum and relativity theories, however, allowed astronomers to probe the inner workings of the celestial objects. Influenced by German-American physicist Albert Einstein’s (1879–1955) theories of relativity and the emergence of **quantum theory**, Indian-born American astrophysicist Subrahmanyan Chandrasekhar (1910-1995) first articulated the **evolution** of stars into supernova, white dwarfs, neutron stars and accurately predicted the conditions required for the formation of black holes subsequently found in the later half of the twentieth century. The articulation of the stellar evolutionary cycle allowed rapid advancements in cosmological theories regarding the creation of the universe. In particular, American astronomer Edwin Hubble’s (1889–1953) discovery of red shifted spectra from stars provided evidence of an expanding universe that, along with increased understanding of **stellar evolution**, ultimately led to the abandonment of static models of the universe and the formulation of big bang based cosmological models.

In 1932, American engineer **Karl Jansky** (1905–1945) discovered existence of radio waves of emanating from beyond the earth. Janskey’s discovery led to the birth of radio astronomy that ultimately became one of the most productive means of astronomical observation and spurred continuing studies of the Cosmos across all regions of the **electromagnetic spectrum**.

Profound questions regarding the birth and death of stars led to the stunning realization that, in a real sense, because the heavier atoms of which he was comprised were derived from nucleosynthesis in dying stars, man too was a product of stellar evolution. After millennia of observing the Cosmos, by the dawn of the twenty-first century, advances in astronomy allowed humans to gaze into the night sky and realize that they were looking at the light from stars distant in **space** and time, and that they, also, were made from the very dust of stars.

ATLANTIC OCEAN • *see* OCEANS AND SEAS

ATMOPHILE • *see* CHALCOPHILES, LITHOPHILES, SIDEROPHILES, AND ATMOPHILES

ATMOSPHERIC CHEMISTRY

Man lives at the bottom of an ocean of air. We may ordinarily take the atmosphere for granted and focus much more concern on the **weather**. This ocean of air, however, has profound consequences for life on Earth.

The surface density of air is about 0.074 lb/ft^3 (1.184 g/l) and surface pressure is about 14 lb/ft^2 (1 atm). This mass of air presses downward at all times. At a higher altitude, however, both the pressure and the density of air decrease. This explains why passenger jets, which often fly near 40,000 ft (12,192 m) to take advantage of the thin or low-density air, require pressurized cabins. Without them, passengers would not be able to take in enough **oxygen** with each breath.

The atmosphere is generally divided into four zones or layers. Starting at sea level and increasing in altitude, they are the **troposphere** (0–10 mi [0–16.1 km]), the **stratosphere** (10–30 mi [16.1–48.3 km]), the **mesosphere** (30–60 mi [48.3–96.6 km]), and the **thermosphere** (beyond 60 mi [96.6 km]). These altitudes are approximate and depend upon a variety of conditions, and are clearly distinct in both their physical properties (e.g., **temperature**) and their **chemistry**.

The troposphere is the region of air closest to the ground. It is where the **clouds** and storm systems are to be found, and where our weather occurs. The troposphere is in direct contact with effluent chemicals generated by living things. These can range from the **carbon dioxide** and **water** vapor we exhale to industrial or automotive pollutants. In the absence of such compounds, atmospheric chemistry is very simple. Since the splitting of both the nitrogen and oxygen molecules requires a great deal of energy, the atmospheric composition is fairly constant at sea level, and without interfering compounds.

Smog is the term applied to the mixture of nitrous oxides, spent **hydrocarbons**, **carbon** monoxide, and **ozone** that is generated by automobiles and industrial combustion. Smog is the thick brown haze that hovers over large populated areas. This combination of gases is reactive. The addition of water vapor or raindrops, for example, can result in the scrubbing of these compounds from the air but also the generation of nitrous, nitric, and carbonic acid. Ozone is a powerful oxidizing agent and results in the degradation of plastics and other materials. However, it is also capable of reacting with spent hydrocarbons to generate noxious chemicals.

Industrial pollutants, such as sulfur dioxide generated by coal-burning power plants, can generate **acid rain** as the sulfur dioxide is converted to sulfurous and sulfuric acid. Even forest fires contribute a large variety of chemical compounds into the atmosphere and induce chemical reactions. And, the largest of all natural disasters, a volcanic eruption, spews tons of chemical compounds into the troposphere where they react to produce acids and other compounds.

The stratosphere is the home of the ozone layer, which is misleading as it implies a distinct region in the atmosphere that has ozone as the major constituent. Ozone is never more than a minor constituent of the atmosphere, although it is a significant minor constituent. The concentration of ozone achieves its maximum in the stratosphere. It is here that the chemistry occurs that blocks incoming ultraviolet radiation.

The complete spectrum of radiation from the **sun** contains a significant amount of high energy ultraviolet light and the energy of these photons is sufficient to ionize atoms or molecules. If this light penetrated to Earth's surface, life as we know it could not exist as the ionizing radiation would continually break down complex molecules.

Within the ozone layer, this ultraviolet energy is absorbed by a delicate balance of two chemical reactions. The first is the photolytic reaction of molecular oxygen to give atomic oxygen, which subsequently combines with another oxygen molecule to give ozone. The second reaction is the absorption of another photon of ultraviolet light by an ozone molecule to give molecular oxygen and a free oxygen **atom**.

$$O_2 \xrightarrow{h\nu} O+O$$

$$O+O_2 \rightarrow O_3$$

$$O_3 \xrightarrow{h\nu} O_2+O$$

It is the combination of these two reactions that allows the ozone layer to protect the planet. These two reactions actually form an equilibrium with the forward reaction being the formation of ozone and the backwards reaction being the depletion.

$$3O_2 \overset{h\nu}{\leftrightarrows} 2O_3$$

The ozone concentration is thus at a constant and relatively low level. It occurs in the stratosphere because this is where the concentration of gases is not so high that the excited molecules are deactivated by collision, but not so low that the atomic oxygen generated can not find a molecular oxygen with which to react.

In the last half of the twentieth century, the manufacture of chlorofluorocarbons (CFCs) for use as propellants in aerosol sprays and refrigerants has resulted in a slow mixing of these compounds with the stratosphere. Upon exposure to high-energy ultraviolet light, the CFCs break down to atomic chlorine, which interferes with the natural balance between molecular oxygen and ozone. The result is a shift in the equilibrium and a depletion of the ozone level. The occurrence of ozone depletion was first noted over **Antarctica**. Subsequent investigations have demonstrated that the depletion of ozone also occurs over the Arctic, resulting in higher than normal levels of ultraviolet radiation reaching many heavily populated regions of **North America**. This is, perhaps, one of the most important discoveries in atmospheric chemistry and has lead to major changes in legislation in all countries in an attempt to stop ozone depletion.

Beyond the stratosphere, the energy levels increase dramatically and the available radiation is capable of initiating a wide variety of poorly characterized chemical reactions. Understanding all of the complexities of atmospheric chemistry is subject for much ongoing research.

See also Atmospheric composition and structure; Atmospheric pollution; Global warming

ATMOSPHERIC CIRCULATION

The **troposphere**, the lowest 9 mi (15 km) of Earth's atmosphere, is the layer in which nearly all **weather** activity takes place. Weather is the result of complex air circulation patterns that can best be described by going from the general to more localized phenomena.

The prime mover of air above Earth's surface is the unequal heating and cooling of Earth by the **Sun**. Air rises as it is heated and descends as it is cooled. The differences in air pressure cause air to circulate, which results in the creation of **wind**, **precipitation**, and other weather related features.

Earth's **rotation** also plays a role in air circulation. Centrifugal force, friction and the apparent Coriolis force are responsible for the circular nature of its flow, as well as for erratic eddies and surges.

On a global scale, there are three circulation belts between the equator and each pole. From 0° to 30° **latitude**, the trade winds, or tropical easterlies, flow toward the equator and are deflected to the west by the earth's rotation as they move across the earth's surface. The winds then rise at the equator, then flow poleward at the tropopause, the boundary between the troposphere and the **stratosphere**. The trade winds descend back to the surface at 30° latitude. At the equator, where air from both trade wind belts rises, the lack of cross-surface winds results in the doldrums, an **area** of calm, which historically has been a bane to sailing vessels.

Between 30° and 60° are the mid-latitude, or prevailing westerlies. The circulation pattern of these wind belts is opposite that of the trades. They flow poleward at the earth's surface, deflecting eastward. They rise at 60°, flow back to the equator, then descend at 30°.

As with the equatorial calm, the earth's surface at 30° North and South has little lateral wind movement since the circulation of the tropical and mid-latitude belts is downward, then outward at this latitude. These calm regions are referred to as the horse latitudes because sailors who were stranded for lack of wind either had to eat their horses or throw them overboard to lighten the load.

The third set of circulation belts, the polar easterlies, range from 60° to 90° latitude at both ends of the earth and flow in the same pattern as the tropical easterlies.

This global circulation scheme is only the typical model. Other forces complicate the actual flow. Differences in the type and elevation of surface features have widespread effects.

The jet streams, high-speed winds blowing from the west near the tropopause, play a significant role in determining the weather. The northern and southern hemispheres each have two **jet stream** wind belts. The polar front jet stream is the stronger of the two. It flows eastward to speeds of 250 mph

(400 kph) at the center and receives its energy from an accumulation of solar radiation. The subtropical jet stream is weaker and receives its force from an accumulation of westerly momentum.

The monsoons of **Asia** are a result of a combination of influences from the large Asian land mass and the movements of the inter-tropical front, which straddles the equator. From June to September, when the front runs north of the equator, warm moist winds are drawn northward, bringing heavy rains to India and Southeast Asia. From December to February, the front runs slightly south of the equator, drawing dry cooler air off of the Himalayas and out to sea.

On a more local level, air movements occur in the form of interacting air masses and frontal systems. Low-pressure cyclones and high-pressure anticyclones travel from the west to east. Low-pressure cells are responsible for instability in the weather, with cold and warm fronts radiating from the center of the cell. These fronts represent the interface of cold and warm air masses, which develop into storms.

Cold fronts are more active than warm fronts. The upward angle of the cold front line opposes the direction in which it moves, creating friction between the surface and the air, and causing a steeper pressure gradient. The rain band is narrower, but the cumulonimbus **clouds** that form hold a greater amount of energy and a greater potential for violent weather than the altostratus clouds associated with warm front activity.

Within each cyclonic system are even smaller cyclones. Each storm cell along a front is a cyclone in its own right. In addition to producing heavy rain, hail, high winds and electrical activity, these cells occasionally can produce tornadoes—destructive, whirling funnel-shaped clouds that stretch from the base of a storm cell to the ground. Tornadoes are the most powerful cyclones known on Earth.

Independent of air mass and frontal systems are hurricanes, also known as typhoons or cyclones. These tropical cyclones generate over warm moist ocean surfaces. The rising heat and moisture builds into a massive storm that can extend 1000 mi (1,600 km).

A hurricane tracks westward and will decay when the creative factors are eliminated. This occurs rapidly as the storm travels over land or more gradually as it encounters lower ocean surface temperatures. A lower tropopause in higher latitudes can also reduce the storm's mass.

An accurate understanding of atmospheric circulation began to emerge during the 1830s when Gustave de Coriolis put forth the theory that as Earth rotates, an object will appear to move in a deflected path. About twenty years later, American William Ferrel mathematically proved the Coriolis theory, establishing what became known as **Ferrel's law**.

The ability to make regular unmanned balloon soundings of the atmosphere in the late 1890s and early 1900s made it possible for new details to emerge. A group of Scandinavian meteorologists under the guidance of Vilhelm Bjerknes took full advantage of this new knowledge to develop mathematical and laboratory models of air mass properties.

Bjerknes first proposed the existence of air masses. His son Jacob went on to demonstrate the frontal systems that separate the air masses. Carl-Gustaf Rossby discovered the jet streams and hypothesized detailed movements and countermovements in the circulation complex.

Atmospheric circulation is a simple process with complex results. It is a system of cells within cells. When we observe leaves swirling in the shadow of a building or a bird soaring on an updraft of warm air, the same principles are at work as with larger global units of the same circulation system. It is a system that is worldwide, that reacts to everything it encounters, and that is even interactive with itself.

See also Air masses and fronts; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pollution; Atmospheric pressure

ATMOSPHERIC COMPOSITION AND STRUCTURE

During most of history, Earth's atmosphere was regarded as little more than a mass of air and **clouds**. Simple observations from the ground yielded little more than a basic understanding of the atmosphere's characteristics.

Manned balloon ascents in the late 1700s and early 1800s were restricted to about 5 miles (8 km), the limit of life-supporting **oxygen**. There were also risks to human life. From a practical standpoint, it was difficult to make widespread observations over **space** and time.

Breakthroughs in atmospheric research came as new inventions made it possible to obtain information from unmanned balloon flights. The first of these was the theodolite, a viewing instrument used to survey distances and angles, invented by Gustave Hermite in 1896. This device increased the range to which a ground observer could follow a balloon's ascent pattern. The information-gathering packages delivered to the atmosphere by balloons became known as radiosondes, with each balloon journey referred to as a sounding. The maximum height at which the atmosphere will sustain a balloon is about 28 miles (35 km).

In 1893, George Besancon developed a recording thermometer and barometer capable of making in-flight observations during unmanned ascents. Beginning in 1897, Léon Phillipe Teisserenc de Bort made improvements to these instruments at an observatory he established near Paris. Of equal importance, this was the first organized effort to obtain repeated readings of high-altitude phenomena.

It was generally known that temperatures decreased with elevation at a rate of about 33.8°F (18.6°C) per 590 feet (180 m). Until de Bort, it was assumed that this rate continued out into space. His observations revealed, however, that temperatures first level off, then increase, beginning at about 8 miles (14 km). This warm region is located only a few kilometers beyond the highest mountain peaks and the upper limit of regular cloud formation.

In 1908, de Bort's observations led him to divide the atmosphere into two layers, the lower being the **troposphere** and the upper being the **stratosphere**. The **area** where the two meet, where the **temperature** begins to modify, he named the *tropopause*.

Eventually, scientists discovered that the atmosphere consists of several layers, not just two. The warm region, it has been found, continues to a level for about 28 miles (45 km). The temperature starts at about –76°F (–60°C) at the tropopause and exceeds 32°F (0°C) at about 28 miles (45 km). Beyond this, the temperature drops again to about –130°F (–90°C) at about 50 miles (80 km). This area has been called the stratopause, but it is also known as the **mesosphere**. This area is where most meteors disintegrate as they approach the earth.

Above the stratopause, at about 62 miles (100 km), the temperature rises sharply again to 212°F (100°C) and continues to rise to levels that can only be theoretically estimated, perhaps 1200° K. This area is called the **thermosphere**.

In the thermosphere, attention shifts from temperature variations to other phenomena. This layer is characterized by highly energized particles (cosmic rays), which enter from outer space and became electronically charged. The result is the **aurora borealis** in the Northern Hemisphere and the aurora australis in the Southern Hemisphere. Both occur at about 20°–25° **latitude** and at heights of 50–190 miles (80–300 km).

The **ionosphere** coincides with, but is not confined to, the thermosphere. Its only distinguishing property is its layers of ionized gases that reflect radio waves, as opposed to other atmospheric regions, which do not. It exists from 50 miles (80 km) upward to 620 miles (1,000 km) and beyond. The ionosphere is influenced greatly by solar activity, which can rearrange or eliminate the reflective layers.

The exosphere begins at about 310 miles (500 km). Here the atmospheric components lose their molecular structure and become atomic in nature. These components cannot be considered gaseous beyond this point.

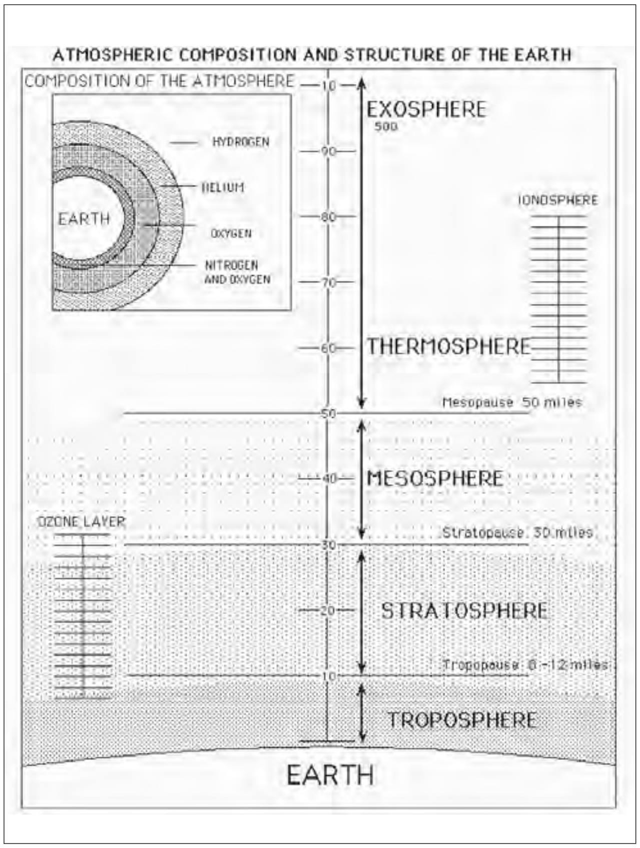
Beyond 620 miles (1,000 km), particle structures further degrade into electrons and protons. The earth's **gravity** gives way to magnetic fields as the dominant distributor of particles. The Van Allen belts at 2,500 miles (4,000 km) and at 12,400 miles (20,000 km) mark the outer limit of the magnetosphere, the most remote known sphere of Earth's influence.

Far beyond the limits of balloon flight, knowledge of the upper atmosphere has been made possible by increasingly high airplane flights and orbiting satellites.

Overall, the atmosphere's gaseous composition consists of 78% nitrogen, 21% oxygen, and a 1% mixture of minor gases dominated by argon. This composition not only sustains life, but is also determined by it. Also, there is a general distribution of dust particles carried from Earth's surface or entering from space.

Recently, scientists have been giving attention to two areas of atmospheric research. Concern has been raised over the destruction of the ozone layer (near the stratospheric warm region), which absorbs ultraviolet radiation, by the introduction of chlorofluorocarbons (CFCs) by man.

A new area of research involves exploration of atmospheres of neighboring planets. With an expanding **solar system**, the dense atmosphere of Venus may hold clues to Earth's atmospheric past, while the thin atmosphere of Mars may be a clue to its future.



Structure and composition of the atmosphere.

See also Atmospheric circulation; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pollution; Atmospheric pressure; Ozone layer and hole dynamics

ATMOSPHERIC INVERSION LAYERS

Whenever an anomaly exists in the atmosphere in which an increase in **temperature**, **humidity**, or **precipitation** occurs where a decrease would be expected, there is an inversion, or reversal. An atmospheric inversion most commonly refers to temperature inversion where the temperature increases rather than decreases with increasing altitude.

Normally air temperature decreases with altitude at a rate of about 33.8° F (1° C) per 59 feet (180 m) because since the Sun's heating effect is greatest at the Earth's surface. There are three factors that alter this rate, causing the temperature to rise within the first few hundred meters of the ground. Inversions can occur as a result of radiative, or direct, cooling from the earth's surface. This occurs at night when the ground cools more rapidly than the air above it. The effects of an inversion are thus greatest during early morning, usually the coolest part of the day. Inversions also occur as a result of subsidence (sinking) of air in an anticyclone, or high pressure system, where the descending air warms adiabatically, that is,

Denver's "brown cloud," the haze of air pollution that hangs over the city, is kept in place by atmospheric inversion layers. © *Ted Spiegel/Corbis. Reproduced by permission.*

within itself, while the ground remains cool. High pressure systems have the stability that inversion layers require. Finally, movement of air can create an advective inversion. For instance, if a warm air mass moves over a body of **water** or over snow cover, an inversion will occur.

Inversion layers block the upward movement of air, trapping moisture and natural and man-made pollutants near the ground. The result is **fog** and **smog**. The lower the inversion ceiling, the more concentrated the accumulation of moisture and particulates. Some of the most serious episodes of smog or fog occur in mountainous areas, especially where a city (e.g., Denver, Colorado) or industrial site is located. In places in the San Fernando Valley in California, the polluted air is trapped both vertically and horizontally.

The mere presence of a city or factory often creates a microclimate of its own, creating a pocket of warm air within the cool ground layer. Smoke from a stack, instead of escaping upward or laterally, will descend to the ground, delivering a direct dose of pollution to residents of the **area**.

See also Atmospheric composition and structure; Atmospheric lapse rate; Atmospheric pollution; Environmental pollution; Greenhouse gases and greenhouse effect; Meteorology; Troposphere and tropopause

ATMOSPHERIC LAPSE RATE

The atmospheric lapse rate describes the reduction, or lapse of air **temperature** that takes place with increasing altitude. Lapse rates related to changes in altitude can also be developed for other properties of the atmosphere.

In the lower regions of the atmosphere (up to altitudes of approximately 40,000 feet [12,000 m]), temperature decreases with altitude at a fairly uniform rate. Because the atmosphere is warmed by conduction from Earth's surface, this lapse or reduction in temperature normal with increasing distance from the conductive source.

Although the actual atmospheric lapse rate varies, under normal atmospheric conditions the average atmospheric lapse rate results in a temperature decrease of 3.5°F (1.94°C) per 1,000 feet (304 m) of altitude.

The measurable lapse rate is affected by the moisture content of the air (**humidity**). A dry lapse rate of 5.5°F (3.05°C) per 1,000 feet (304 m) is often used to calculate temperature changes in air not at 100% relative humidity. A wet lapse rate of 3°F (1.66°C) per 1,000 feet (304 m) is used to calculate the temperature changes in air that is saturated (i.e., air at 100% relative humidity). Although actual lapse rates do not strictly follow these guidelines, they present a model sufficiently accurate to predict temperate changes associated with updrafts and **downdrafts**. This differential lapse rate (dependent upon both difference in conductive heating and adiabatic expansion and compression) results in the formation of warm downslope winds (e.g., Chinook winds, Santa Anna winds, etc.).

The atmospheric lapse rate, combined with adiabatic cooling and heating of air related to the expansion and compression of atmospheric gases, present a unified model explaining the cooling of air as it moves aloft and the heating of air as it descends downslope.

Atmospheric stability can be measured in terms of lapse rate (i.e., the temperature differences associated with vertical movement of air). A high lapse rate indicates a greater than normal change of temperature associated with a change in altitude and is characteristic of an unstable atmosphere.

Although the atmospheric lapse rate (also known as the environmental lapse rate) is most often used to characterize temperature changes, many properties (e.g., **atmospheric pressure**) can also be profiled by lapse rates.

See also Air masses and fronts; Land and sea breeze; Seasonal winds

ATMOSPHERIC POLLUTION

Atmospheric pollution (also commonly called air pollution) is derived chiefly from the spewing of gasses and solid particulates into the atmosphere. Many pollutants—dust, pollen, and **soil** particles—occur naturally, but most air pollution, as the term is most commonly used and understood, is caused by human activity. Although there are countless sources of air pollution, the most common are emissions from the burning of **hydrocarbons** or fossil **fuels** (e.g., **coal** and oil products). Most of the world's industrialized countries rely on the burning of fossil fuels; power plants heat homes and provide **electricity**, automobiles burn gas, and factories burn materials to create products.

Air pollution is a serious global problem, and is especially problematic in large urban areas such as Mexico City, Mexico, and Athens, Greece. Many people suffer from serious illnesses caused by **smog** and air pollution in these areas. Plants, buildings, and animals are also victims of a particular type of air pollution called **acid rain**. Acid rain is caused by airborne sulfur from burning coal in power plants and can be transported in rain droplets for thousands of miles. Poisons are then deposited in streams, **lakes**, and soils, causing damage to wildlife. In addition, acid rain eats into concrete and other solid structures, causing buildings to slowly deteriorate.

Scientists study air pollution by breaking the particulates into two different categories of gasses: permanent and variable. The most common of the stable gasses are nitrogen at 78%, and **oxygen** at 21% of the total atmosphere. Other highly variable gasses are **water** vapor, **carbon dioxide**, methane, **carbon** monoxide, sulfur dioxide, nitrogen dioxide, **ozone**, ammonia, and hydrogen sulfide.

Output of variable gasses increases with the growth of industrialization and population. The benefits of progress cost people billions of dollars each year in repairing and preventing air pollution damage. This includes health care and the increased maintenance of structures such as the Great Pyramids of Egypt that are crumbling, in part due to air pollution.

The effects of air pollution have to be carefully measured because the build-up of particulates depends on atmospheric conditions and a specific area's emission level. Once pollutants are released into the atmosphere, **wind** patterns make it impossible to contain them to any particular region. This is why the effects of pollution from major oil fires in the Middle East are measurable in **Europe** and elsewhere. On the other hand, terrestrial formations such as mountain ridges can act as natural barriers. The terrain and **climate** of a particular **area** (e.g., Denver, Houston, and Los Angeles) can also help promote or deflect air pollution. Specifically, **weather** conditions called thermal inversions can trap the impurities and cause them to build up until they have reached dangerous levels. A thermal inversion is created when a layer of warm air settles over a layer of cool area closer to the ground. It can stay until rain or wind dissipates the layer of stationary warm air.

The United States government plays an active role in establishing safe and acceptable levels of clean air. In 1967, Congress passed the Air Quality Act that set forth outlines for air quality standards. The Environmental Protection Agency released the first nationwide survey on air pollution in 1989 after Congress passed a law requiring the report. In most cases, it is up to individual states, however, to enforce air pollution controls and meet federally mandated goals. In addition, states may set their own clean air standards that are more strict than those established at the federal level. For example, in 1989, California adopted a radical air pollution reduction plan that essentially requires each region to drastically reduce current levels of air pollution. Even as early as 1970, California adopted more stringent standards for motor-vehicle emissions.

Government regulations have shown moderate success. Since 1970, emissions of sulfur oxide, carbon monoxide, **lead**, and hydrocarbons have decreased by approximately 30% while nitrogen oxide output has been reduced by approximately 10%. Cars are now required to have pollution-control devices called catalytic converters, and most power plants are equipped with filters called scrubbers to remove sulfur oxides.

In addition to atmospheric pollution, indoor air pollution also poses special hazards. Some man-made sources of indoor air pollutants include asbestos particulates and formaldehyde vapors—once common building materials now thought to cause cancer. Lead paint is also a problem in older buildings, but its use has been phased out. Other sources of man-made indoor air pollution include improperly vented stoves and heaters, tobacco smoke, and emissions or spillage from pesticides, aerosol sprays, solvents, and disinfectants.

See also Atmosphere; Geochemistry; Global warming; Greenhouse gases and greenhouse effect; Petroleum, economic uses of; Rate factors in geologic processes; Weathering and weathering series

ATMOSPHERIC PRESSURE

Aristotle, whose teachings sometimes otherwise inhibited the advancement of science, was right on target in his belief that the atmosphere surrounding the Earth had weight. Moreover, Aristotle stated that as air density decreased, it would be possible for an object to move faster. However, he did not believe in the concept of a vacuum because the absence of an atmosphere meant an object could move infinitely fast, and since infinite speed was not possible, a vacuum that allowed infinite speed was not considered possible either. Galileo disputed some of Aristotle's contentions. In 1638, Galileo published a book in which he asserted a vacuum was possible. But Galileo did not hold that air had a weight that could exert a pressure, even though his own experiments showed clearly that air exerted a force on objects. This was perhaps because he discounted everything Aristotle said, even when he happened to be right. Consequently, the thermometer Galileo invented was inaccurate because it did not take the effect of air pressure into account. **Otto von Guericke** became interested in air pressure because of Galileo's comments on the subject. In a public demonstration in 1657, Guericke became the first to use an air pump and create a vacuum, thus ending the debate on whether one could exist.

In 1643, in Florence, Italy, **Evangelista Torricelli** furthered Guericke's work. Filling a narrow tube with mercury and upending it in a bowl of mercury, Torricelli found that only a portion of the tube emptied. He correctly surmised that the atmospheric pressure upon the mercury in the bowl kept the tube from draining completely, and the vacant **area** at the top of the tube was a vacuum. He noticed the height of the column of mercury fluctuated from day to day, indicating that the atmospheric pressure changed. The barometer, a device to measure the pressure of the atmosphere, was born, yet that name wouldn't exist for another 20 years.

Fig. 10.

Aneroid barometer. ***National Oceanic and Atmospheric Administration (NOAA).***

Mathematician Blaise Pascal duplicated the experiments of Torricelli, and he expanded on them. In 1648, Pascal, who suffered from ill health, had his brother-in-law make measurements of air pressure at various altitudes on a mountain. As expected, the higher the altitude, the less pressure registered on the barometer. Obviously, the weight of the air at the surface of the Earth was greater because it has to support the atmosphere above it. Robert Boyle duplicated Torricelli's experiment as well. In 1660, Boyce placed his mercury-filled tube in a container and removed the surrounding air, creating a vacuum. As the air was removed, the column of mercury dropped. When completely evacuated, the mercury showed zero air pressure in the container. It was Boyle who coined the word "barometer" in 1665.

Today, it is known that the weight of Earth's atmosphere is more than five quadrillion tons. The weight of air pressing down on one's shoulders is about one ton, but we aren't flattened because we are supported on all sides by an equal amount of pressure. The normal barometric pressure at sea level, equal to one atmosphere (1 atm) of pressure equals 14.7 psi (pounds per square inch), or 760 mm (29.92 inches) of mercury.

See also Air masses and fronts; Weather forecasting

ATOLL OR ANNULAR ISLAND • *see* GUYOTS AND ATOLLS

ATOM

Atoms and the subatomic particles that comprise them, are the elementary building blocks of material substances. Although the term atom, derived from the Greek word *atomos*, meaning indivisible, would seem inappropriate for an entity that, as science has established, is divisible, the word atom still makes sense, because, depending on the context, atoms can still be regarded as indivisible. Namely, once the nucleus is split, the atom loses its identity and subatomic particles. Protons, electrons, neutrons, are all the same—regardless of the type of atom or element—it is only their numbers and unique combinations that make for different atoms. Accordingly, an atom is the smallest particle of an element.

Atoms share many characteristics with other material objects: they can be measured, and they also have mass and weight. Because traditional methods of measuring are difficult to use for atoms and subatomic particles, scientists have created a new unit, the atomic mass unit (amu), which is defined as the one-twelfth of the mass of the average **carbon** atom.

The principal subatomic particles are the protons, neutrons, and the electrons. The nucleus, the atom's core, consists of protons, which are positively charged particles, and neutrons, particles without any charge. Electrons are negatively charged particles with negligible mass that orbit around the nucleus. An electron's mass is so small that it is usually given a 0 amu value in atomic mass units, compared to the value of 1 amu assigned to neutrons and protons (neutrons do carry slightly more mass than protons and neither exactly equals 1 amu—but for purposes of this article the approximate values will suffice). In fact, as the nucleus represents more than 99% of an atom's mass, it is interesting to note that an atom is mostly **space**. For example, if a hydrogen atom's nucleus were enlarged to the size of a **marble**, the atom's diameter (to the electron orbit) would be around 0.5 mi (800 m).

At one time, scientists asserted that electrons circled around the nucleus in planet-like orbits. However, because all subatomic particles, including electrons, exhibit wave-like properties, it is makes no sense to conceptualize the movement of electrons as like planetary **rotation**. Scientists therefore prefer terms like "electron cloud patterns," or "shells," indicating an electron's position and/or pattern of movement in relation to the nucleus. Thus, for example, hydrogen has one electron in its innermost, lowest energy shell (a shell is also an energy level); lithium—with three electrons—has two shells, with inner most, lowest energy shell contains two electrons that one electron exists in a more distant shell or higher potential energy level. The elements exhibit four distinctive shapes of shell—designated *s, p, d,* and *f* orbitals.

While subatomic particles are generic and interchangeable, in combination they determine an atom's identity. For example, we know that an atom with a nucleus consisting of one proton must be hydrogen (H). An atom with two protons is always a helium (He) atom. Thus, we see that the key to an atom's identity is to be found in the atom's inner structure. In addition, a electrically balanced chemical element is an instance of atomic electronic equilibrium: for example, in an electrically balanced chemical element, the number of positively charged particles (protons) always equals the number of negatively charged particles (electrons). A loss or gain of electrons results in a net charge and the atom becomes an ion.

Although the number of protons determines the name (type) of atom, each atom may be heavier or lighter depending on the number of neutrons present. Atoms of the same element with different mass (reflecting differing numbers of neutrons) are isotopes.

Research into the atom's nucleus has uncovered a variety of subatomic particles, including quarks and gluons. Considered by some researchers the true building blocks of matter, quarks are the particles that form protons and neutrons. Gluons hold smaller clusters of quarks together.

The atom is best characterized by the laws and terminology or quantum **physics**. On a larger scale, chemists study reactions, the behavior of elements in interaction, and reactions, such as those leading to the formation of chemical compounds. Such reactions involve the transfer of electrons and/or the sharing of electrons in atomic bonds.

For example, the formation of sodium chloride, also known as table salt, would be impossible without specific changes at a subatomic level. The genesis of sodium chloride (NaCl) starts when a sodium (Na) atom, which has 11 electrons, loses an electron. With 10 electrons, the atom now has one more proton than electrons and thus becomes a net positively charged sodium ion Na^+ (a positively charged ion is also known as a cation. Chlorine becomes a negatively charged anion by accepting a free electron to take on a net negative charge. The newly acquired electron goes into the outer shell, also known as the valence shell that already contains seven electrons. The addition of the eighth electron to the chlorine atom's outmost shell fulfills the octet rule and allows the atom—although now a negatively charged chlorine ion (Cl^-)—to be more stable. The electrical attraction of the sodium cations for the chlorine anion results in an ionic bond to form salt. **Crystals** of table salt consist of equal numbers of sodium cations and chlorine anions, cation-anion pairs being held together by a force of electrical attraction.

The octet rule is used to describe the attraction of elements toward having, whenever possible, eight valence-shell electrons (four electron pairs) in their outer shell. Because a full outer shell with eight electrons is relatively stable, many atoms lose or gain electrons to obtain an electron configuration like that of the nearest noble gas. Except for helium (with a filled 1s shell), noble gases have eight electrons in their valence shells.

Interestingly, not long after scientists realized that at the level of the nucleus an atom is divisible, transmutation, or the old alchemic dream of turning one substance into another, became a reality. Fission and fusion are tranformative processes that, by altering the nucleus, alter the element. For example, scientists even succeeded in creating gold by bombarding platinum-198 with neutrons to create platinum-199 that then decays to gold-199. Although clearly demonstrating the reality of transmutation, this particular transmutation (a change in the nuclear structure that changes one element into another) is by no means an easy or cheap method of producing gold. Quite the contrary, because platinum, particularly the platinum-199 isotope, is more expensive than gold produced. Regardless, the symbolic value of the experiment is immense, as it shows that the idea, developed by ancient alchemists and philosophers, of material transmutation—accomplished at the nuclear level—does not essentially contradict our understanding of the atom.

Natural transformations also exist—as with the decay of Carbon-14 to nitrogen—accomplished by the nuclear transformation of one Carbon-14 neutron into a proton.

See also Atomic mass and weight; Atomic number; Atomic theory; Chemical bonds and physical properties; Chemical elements

ATOMIC MASS AND WEIGHT

The atomic mass of an **atom** (i.e., a specific isotope of an element) is measured in comparison with the mass of one atom of carbon-12 (^{12}C) that is assigned a mass of 12 atomic mass units (amu). Atomic mass is sometimes erroneously confused with atomic weight—the obsolete term for relative atomic mass. Atomic weights, however, are still listed on many Periodic tables.

A mole of any element or compound (i.e., 6.022×10^{23}—Avogadro's number—atoms or molecules) weighs its total unit atomic mass (formerly termed atomic weight) in grams. For example, **water** (H_2O) has a molar mass (the mass of 6.022×10^{23} water molecules) of approximately 18 grams (the sum of 2 hydrogen atoms, each with an atomic mass of 1.0079 amu, bonded with one **oxygen** atom with an atomic mass of 15.9994 amu).

In general usage if a specific isotope or isotope distribution is specified when using atomic mass, the natural percentage distribution of isotopes of that element is assumed. Periodic tables, for example usually list the atomic weights of individual elements based upon the natural distribution of isotopes of that element.

Mass is an intrinsic property of matter. Weight is a measurement of gravitational force exerted on matter.

In a series of papers published between 1803 and 1805 English physicist and chemist John Dalton (1766–1844) emphasized the importance of knowing the weights of atoms and outlined an experimental method for determining those weights.

The one problem with Dalton's suggestion was that chemists had to know the formulas of chemical compounds before they could determine the weights of atoms. But they had no way of knowing chemical formulas without a dependable table of atomic weights.

Dalton himself had assumed that compounds always had the simplest possible formula: HO for water (actually H_2O), NH for ammonia (actually NH_3), and so on. Although incorrect, this assumption allowed him to develop the concept of atomic weights, but, because his formulas were often wrong, his work inevitably resulted in incorrect values for most of the atomic weights. For example, he reported 5.5 for the atomic weight of monatomic oxygen and 4.2 for monatomic nitrogen. The correct values for those weights are closer to 16 and 14.

The first reasonably accurate table of atomic weights was produced by Swedish chemist Jöns Jacob Berzelius (1779–1848) in 1814. This table had been preceded by nearly a decade of work on the chemical composition of compounds. Once those compositions had been determined, Berzelius could use this information to calculate correct atomic weights.

In this process, Berzelius was faced with a decision that confronted anyone who tried to construct a table of atomic weights: What element should form the basis of that table and what would be the atomic weight of that standard element?

The actual weights of atoms are, of course, far too small to use in any table. The numbers that we refer to as atomic weights are all *ratios*. To say that the atomic weight of oxygen is 16, for example, is only to say that a single oxygen atom is 16 times as heavy as some other atom whose weight is somehow chosen as 1, or eight times as heavy as another atom whose weight has been chosen as 2, or one-half as heavy as another atom whose weight was selected to be 32, and so on.

Dalton had made the logical conclusion to use hydrogen as the standard for his first atomic table and had assigned a value of 1 for its atomic weight. Because hydrogen is the lightest element, this decision assures that all atomic weights will be greater than one.

The problem with Dalton's choice was that atomic weights are determined by measuring the way elements combine with each other, and hydrogen combines with relatively few elements. So, using Dalton's system, determining the atomic weight of another element might require a two-or three-step process.

Berzelius thought it made more sense to choose oxygen as the standard for an atomic weight table. Oxygen forms compounds with most other elements whose atomic weights can, therefore, be determined in a single step. He arbitrarily assigned a value of 100 as the atomic weight of oxygen. Other chemists agreed that oxygen should be the atomic weight standard, but used other values for its weight.

Berzelius continued working on atomic weights until, in 1828, he produced a table with values very close to those accepted today.

With the introduction of the concept of molecules (e.g., that the correct formula for water was H_2O) by Stanislao Cannizarro in 1858, it also became possible to calculate molecular weights. The molecular weight of any compound is equal to the sum of the weights of all the atoms in a molecule of that compound.

The most precise work on atomic weights during the nineteenth century was that of the Belgian chemist Jean Servais Stas (1813–1891). For over a decade, Stas recalculated Berzelius' weights, producing results that were unchallenged for nearly half a century.

An even higher level of precision was reached in the work of the American chemist Theodore William Richards (1868–1918). Richards spent more than 30 years improving methods for the calculation of atomic weights and redetermining those weights. Richards was awarded the Nobel Prize in chemistry in 1914 for these efforts.

The debate as to which element was to be used as the standard for atomic weights extended into the twentieth century, with the most popular positions being hydrogen with a weight of 1 or oxygen with a weight of 16. Between 1893 and 1903, various chemical societies finally agreed on the latter standard.

The controversy over standards was complicated by the fact that, over time, physicists and chemists began to use different standards for the atomic weight table and, thus, recognized slightly different values for the atomic weights of the elements. This dilemma was finally resolved in 1961 when chemists and physicists agreed to set the atomic weight of the carbon-12 isotope as 12.0000 as the standard for all atomic weights.

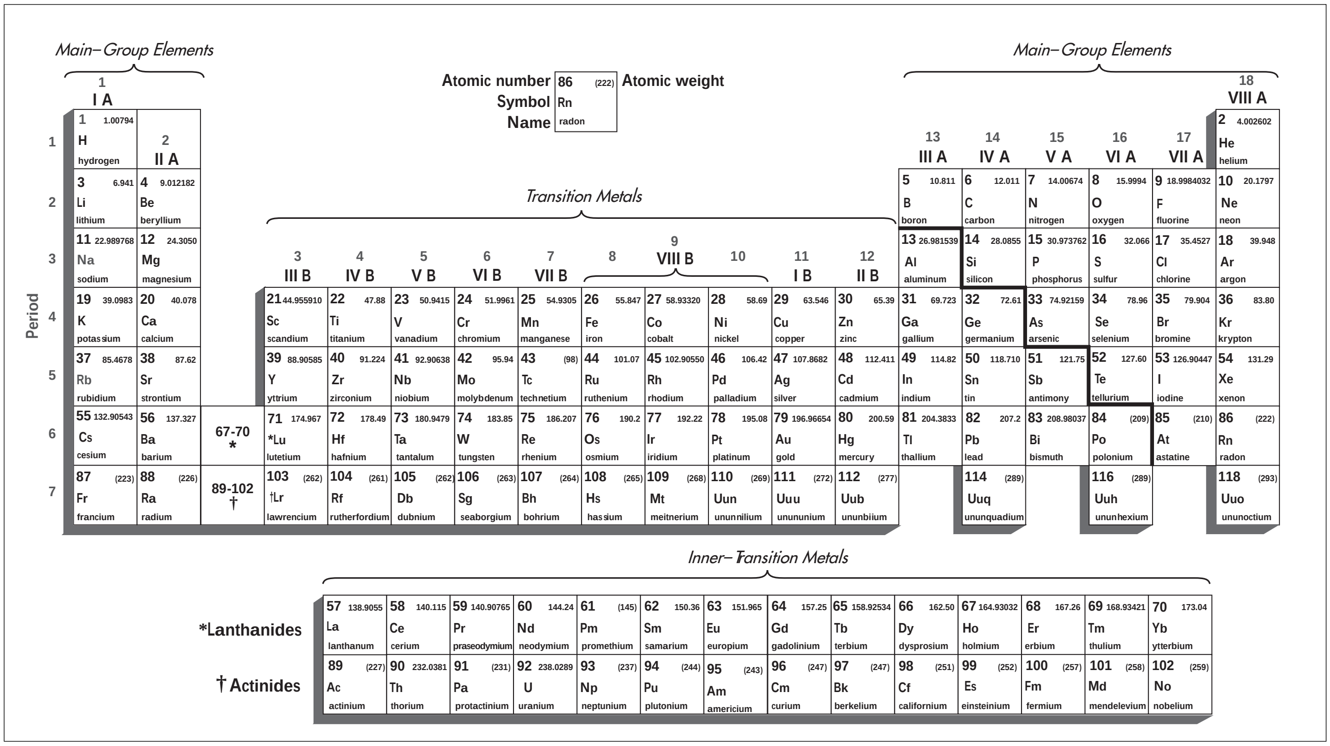
See also Atomic number; Atomic theory; Chemical bonds and physical properties; Chemical elements; Chemistry; Minerals

ATOMIC NUMBER

Atomic number is defined as the number of protons in the nucleus of an **atom**. This concept was historically important because it provided a theoretical basis for the periodic law. Dmitri Mendeleev's discovery of the periodic law in the late 1860s was a remarkable accomplishment. It provided a key-organizing concept for the chemical sciences. One problem that remained in Mendeleev's final analysis was the inversion of certain elements in his **periodic table**. In three places, elements arranged according to their chemical properties, as dictated by Mendeleev's law, are out of sequence according to their atomic weights.

The solution to this problem did not appear for nearly half a century. Then, it evolved out of research with x rays, discovered in 1895 by Wilhelm Röntgen. Roentgen's discovery of this new form of electromagnetic radiation had inspired a spate of new research projects aimed at learning more about x rays themselves and about their effects on matter. Charles Grover Barkla, a physicist at the Universities of London and Cambridge, initiated one line of x-ray research. Beginning in 1903, he analyzed the way in which x rays were scattered by gasses, in general, and by elements, in particular. He found that the higher an element was located in the periodic table, the more penetrating the rays it produced. He concluded that the x-ray pattern he observed for an element was associated with the number of electrons in the atoms of that element.

Barkla's work was brought to fruition only a few years later by the English physicist H.G.J. Moseley. In 1913, Moseley found that the x-ray spectra for the elements changed in a simple and regular way as one moved up the periodic table. Moseley, like Barkla, attributed this change to the number of electrons in the atoms of each element and, thus, to the total positive charge on the nucleus of each atom. (Because atoms are electrically neutral, the total number of positive charges on the nucleus must be equal to the total number of negatively charged electrons.)



Main–Group Elements

Transition Metals

Inner–Transition Metals

Atomic number 86 (222) Atomic weight
Symbol Rn
Name radon

Period	1 I A	2 II A		3 III B	4 IV B	5 V B	6 VI B	7 VII B	8	9 VIII B	10	11 I B	12 II B	13 III A	14 IV A	15 V A	16 VI A	17 VII A	18 VIII A
1	1 1.00794 H hydrogen																		2 4.002602 He helium
2	3 6.941 Li lithium	4 9.012182 Be beryllium												5 10.811 B boron	6 12.011 C carbon	7 14.00674 N nitrogen	8 15.9994 O oxygen	9 18.9984032 F fluorine	10 20.1797 Ne neon
3	11 22.989768 Na sodium	12 24.3050 Mg magnesium												13 26.981539 Al aluminum	14 28.0855 Si silicon	15 30.973762 P phosphorus	16 32.066 S sulfur	17 35.4527 Cl chlorine	18 39.948 Ar argon
4	19 39.0983 K potassium	20 40.078 Ca calcium		21 44.955910 Sc scandium	22 47.88 Ti titanium	23 50.9415 V vanadium	24 51.9961 Cr chromium	25 54.9305 Mn manganese	26 55.847 Fe iron	27 58.93320 Co cobalt	28 58.69 Ni nickel	29 63.546 Cu copper	30 65.39 Zn zinc	31 69.723 Ga gallium	32 72.61 Ge germanium	33 74.92159 As arsenic	34 78.96 Se selenium	35 79.904 Br bromine	36 83.80 Kr krypton
5	37 85.4678 Rb rubidium	38 87.62 Sr strontium		39 88.90585 Y yttrium	40 91.224 Zr zirconium	41 92.90638 Nb niobium	42 95.94 Mo molybdenum	43 (98) Tc technetium	44 101.07 Ru ruthenium	45 102.90550 Rh rhodium	46 106.42 Pd palladium	47 107.8682 Ag silver	48 112.411 Cd cadmium	49 114.82 In indium	50 118.710 Sn tin	51 121.75 Sb antimony	52 127.60 Te tellurium	53 126.90447 I iodine	54 131.29 Xe xenon
6	55 132.90543 Cs cesium	56 137.327 Ba barium	67-70 *	71 174.967 *Lu lutetium	72 178.49 Hf hafnium	73 180.9479 Ta tantalum	74 183.85 W tungsten	75 186.207 Re rhenium	76 190.2 Os osmium	77 192.22 Ir iridium	78 195.08 Pt platinum	79 196.96654 Au gold	80 200.59 Hg mercury	81 204.3833 Tl thallium	82 207.2 Pb lead	83 208.98037 Bi bismuth	84 (209) Po polonium	85 (210) At astatine	86 (222) Rn radon
7	87 (223) Fr francium	88 (226) Ra radium	89-102 †	103 (262) †Lr lawrencium	104 (261) Rf rutherfordium	105 (262) Db dubnium	106 (263) Sg seaborgium	107 (264) Bh bohrium	108 (265) Hs hassium	109 (268) Mt meitnerium	110 (269) Uun ununnilium	111 (272) Uuu unununium	112 (277) Uub ununbiium		114 (289) Uuq ununquadium		116 (289) Uuh ununhexium		118 (293) Uuo ununoctium

*Lanthanides	57 138.9055 La lanthanum	58 140.115 Ce cerium	59 140.90765 Pr praseodymium	60 144.24 Nd neodymium	61 (145) Pm promethium	62 150.36 Sm samarium	63 151.965 Eu europium	64 157.25 Gd gadolinium	65 158.92534 Tb terbium	66 162.50 Dy dysprosium	67 164.93032 Ho holmium	68 167.26 Er erbium	69 168.93421 Tm thulium	70 173.04 Yb ytterbium
† Actinides	89 (227) Ac actinium	90 232.0381 Th thorium	91 (231) Pa protactinium	92 238.0289 U uranium	93 (237) Np neptunium	94 (244) Pu plutonium	95 (243) Am americium	96 (247) Cm curium	97 (247) Bk berkelium	98 (251) Cf californium	99 (252) Es einsteinium	100 (257) Fm fermium	101 (258) Md mendelevium	102 (259) No nobelium

The periodic table.

Moseley devised the concept of atomic number and assigned atomic numbers to the elements in such a way as to reflect the regular, integral, linear relationship of their x-ray spectra. It soon came to be understood that the atomic number of an atom is equal to the number of protons in the atom's nucleus.

Moseley's discovery was an important contribution to the understanding of Mendeleev's periodic law. Mendeleev's law was a purely empirical discovery. It was based on properties that could be observed in a laboratory. Moseley's discovery provided a theoretical basis for the law. It showed that chemical properties were related to atomic structure (number of electrons and nuclear charge) in a regular and predictable way.

Arranging the periodic table by means of atomic number also resolved some of the problems remaining from Mendeleev's original work. For example, elements that appeared to be out of place when arranged according to their atomic weights appeared in their correct order when arranged according to their atomic numbers.

See also Atomic mass and weight; Atomic theory; Bohr model; Chemical bonds and physical properties; Geochemistry

ATOMIC THEORY

One of the points of dispute among early Greek philosophers was the ultimate nature of matter. The question was whether the characteristics of matter that can be observed with the five senses are a true representation of matter at its most basic level. Some philosophers thought that they were. Anaxagoras of Klazomenai (c. 498–428 B.C.), for example, taught that matter can be sub-divided without limit and that it retains its characteristics no matter how it is divided.

An alternative view was that of Leucippus of Miletus (about 490 B.C.) and his pupil, Democritus of Abdera (c. 460–370 B.C.). The views of these scholars are preserved in a few fragments of their writings and of commentaries on their teachings. Some writers doubt that Leucippus even existed. In any case, the ideas attributed to them are widely known. They thought that all matter consists of tiny, indivisible particles moving randomly about in a void (a vacuum). The particles were described as hard, with form and size, but no color, taste, or smell. They became known by the Greek word *atomos*, meaning "indivisible." Democritus suggested that, from time to time, atoms collide and combine with each other by means of hook-and-eye attachments on their surfaces.

Perhaps the most effective popularizer of the atomic theory was the Roman poet and naturalist, Lucretius. In his poem *De Rerum Natura* (On the nature of things) Lucretius states that only two realities exist, solid, everlasting particles and the void. This atomistic philosophy was in competition with other ideas about the fundamental nature of matter. Aristotle, for example, rejected Democritus' ideas because he could not accept the concept of a vacuum nor the idea that particles could move about on their own.

In addition, debates between atomists and anti-atomists quickly developed religious overtones. As the natural philosophy of Aristotle was adopted by and incorporated into early Christian theology, anti-atomism became acceptable and "correct," atomism, heretical. In fact, one objective of Lucretius' poem was to provide a materialistic explanation of the world designed to counteract religious superstition rampant at the time.

In spite of official disapproval, the idea of fundamental particles held a strong appeal for at least some philosophers through the ages. The French philosopher Pierre Gassendi (1592–1655) was especially influential in reviving and promoting the idea of atomism. Robert Boyle and Isaac Newton were both enthusiastic supporters of the theory.

Credit for the first modern atomic theory goes to the English chemist, John Dalton. In his 1808 book, *A New System of Chemical Philosophy*, Dalton outlined five fundamental postulates about atoms: 1. All matter consists of tiny, indivisible particles, which Dalton called atoms. 2. All atoms of a particular element are exactly alike, but atoms of different elements are different. 3. All atoms are unchangeable. 4. Atoms of elements combine to form "compound atoms" (i.e., molecules) of compounds. 5. In chemical reactions, atoms are neither created nor destroyed, but are only rearranged.

A key distinguishing feature of Dalton's theory was his emphasis on the weights of atoms. He argued that every **atom** had a specific weight that could be determined by experimental analysis. Although the specific details of Dalton's proposed mechanism for determining atomic weights were flawed, his proposal stimulated other chemists to begin research on atomic weights.

Dalton's theory was widely accepted because it explained so many existing experimental observations and because it was so fruitful in suggesting new lines of research. But the theory proved to be wrong in many of its particulars. For example, in 1897, the English physicist Joseph J. Thomson showed that particles even smaller than the atom, electrons, could be extracted from atoms. Atoms could not, therefore, be indivisible. The discovery of **radioactivity** at about the same time showed that at least some atoms are not unchangeable, but instead, spontaneously decay into other kinds of atoms.

By 1913, the main features of the modern atomic theory had been worked out. The work of Ernest Rutherford, **Niels Bohr** and others, suggested that an atom consists of a central core, the nucleus, surrounded by one or more electrons, arranged in energy levels each of which can hold some specific number of electrons.

Bohr's atomic model marked the beginning of a new approach in constructing atomic theory. His work, along with that of **Erwin Schrödinger**, Louis Victor de Broglie, Werner Karl Heisenberg, Paul Adrien Maurice Dirac, and others showed that atoms could be understood and represented better through mathematics than through physical models. Instead of drawing pictures that show the location and movement of particles within the atoms, modern scientists tend to write mathematical equations that describe the behavior of observed atomic phenomena.

See also Atomic mass and weight; Atomic number; Chemical bonds and physical properties

AURORA BOREALIS AND AURORA AUSTRALIALIS

The Aurora Borealis and Aurora Australialis are electromagnetic phenomena that occur near Earth's polar regions. The Aurora Borealis—also known as the "northern lights" (boreal derives from Latin for "north")—occurs near the northern polar regions. The Aurora Australialis is a similar phenomenon that occurs in southern polar regions.

Auroras are colored and twisting ribbons of light that appear to twist and gyrate in the atmosphere.

Auroras result from the interaction of Earth's **magnetic field** with ionic gas particles, protons, and electrons streaming outward from the **Sun**. Solar storms result in magnetic disturbances that lead to coronal mass ejections (CMEs) of ionic charged particles in solar "winds." As the magnetic particles pass Earth, the plasma streams (streams of charged particles) interact with Earth's magnetosphere (magnetic field). The magnetic interactions excite electron transitions that result in the emission of visible light.

Charged particles may also travel down Earth's magnetic field lines into Earth's **ionosphere**. As the charged particles interact with charged atmospheric gases in Earth's ionosphere, the electrons in the gases move to higher energy states. As the excited electrons return to their ground state, light photons are emitted. The colors of light correspond to particular frequencies and wavelengths generated by the energy of particular electron orbital transmissions, and are unique to different gaseous compounds. **Oxygen** atoms tend to give off red and greenish light. Nitrogen tend to produce wavelengths light in the bluish region of spectrum.

Although they may form anywhere, auroras are usually found in ring like regions (auroral rings or auroral ovals) that surround Earth's poles. Auroral rings or ovals are readily visible from **space**. Auroras are normally associated with the polar regions because it there where the magnetic field lines of Earth converge and are of the highest density.

The auroras also generate high levels of **electricity** that can exceed 100,000 megawatts within a few hours and sometimes interfere with communications equipment and/or signal transmission or reception.

See also Atmospheric chemistry; Atmospheric composition and structure; Atomic theory; Atoms; Bohr model; Chemical elements; Coronal ejections and magnetic storms; Electricity and magnetism; Electromagnetic spectrum; Quantum electrodynamics (QED); Solar sunspot cycles

AUSTRALIA

Of the seven continents, Australia is the flattest, smallest, and except for **Antarctica**, the most arid. Including the southeastern island of Tasmania, the island continent is roughly equal in **area** to the United States, excluding Alaska and Hawaii. Millions of years of geographic isolation from other landmasses accounts for Australia's unique animal species, notably

Aurora Borealis, one of the great wonders of the natural world. ***FMA. Reproduced by permission.***

marsupial mammals like the kangaroo, egg laying mammals like the platypus, and the flightless emu bird. Excluding folded structures (areas warped by geologic forces) along Australia's east coast, patches of the northern coastline and the relatively lush island of Tasmania, the continent is mostly dry and inhospitable.

Australia has been less affected by seismic and orogenic (mountain building) forces than other continents during the past 400 million years. Although seismic (**earthquake**) activity persists in the eastern and western highlands, Australia is the most stable of all continents. In the recent geological past, it has experienced none of the massive upheavals responsible for uplifting the Andes in **South America**, the Himalayas in south **Asia**, or the European Alps. Instead, Australia's **topography** is the result of gradual changes over millions of years.

Australia is not the oldest continent, a common misconception arising from the continent's flat, seemingly unchanged expanse. Geologically, it is the same age as the Americas, Asia, **Africa**, **Europe**, and Antarctica. Australia's **crust**, however, has escaped strong Earth forces in recent geological history, accounting for its relatively uniform appearance. As a result, the continent serves as a window to early geological ages.

About 95 million years ago, tectonic forces (movements and pressures of Earth's crust) split Australia from Antarctica and the southern supercontinent of Gondwanaland. Geologists estimate that the continent is drifting northward at a rate of approximately 18 in (28 cm) per year. They theorize that south Australia was joined to Antarctica at the Antarctic regions of Wilkes Land, including Commonwealth Bay. Over a period of 65 million years, beginning 160 million years ago, Australia's crust was stretched hundreds of miles by tectonics before it finally cleaved from Antarctica.

Testimony to the continental stretching and splitting includes Kangaroo Island off South Australia, made up of volcanic basalts, as well as thick layers of sediment along the coast of Victoria. Other signs are the similar **geology** of the Antarctic Commonwealth Bay and the Eyre Peninsula of South Australia, especially equivalent rocks, particularly gneisses (metamorphic rocks changed by heat and pressure) of identical age. The thin crust along Australia's southern flank in the Great Australian Bight also points to continental stretch.

As it drifts north, the Australian plate is colliding with the Pacific and Eurasian plates, forming a **subduction zone** (an area where one continental plate descends beneath another). This zone, the convergence of the Australian continental plate with Papua New Guinea and the southern Indonesian islands, is studded with volcanos and prone to earthquakes. Yet, Australia is unique in that it is not riven by subduction zones like other continents. There are no upwelling sections of the earth's mantle below Australia (the layer below the crust), nor are there intracontinental rift zones like the East African Rift System which threatens to eventually split Africa apart.

Furthermore, Australia and Antarctica are dissimilar to other landmasses; their shapes are not rough triangles with apexes pointing southward like South America, Africa, and the Indian subcontinent, Gondwanaland's other constituent parts. However, like its sister continents, Australia is composed of three structural units. These include in Western Australia a stable and ancient block of basement **rock** or **craton** as geologists call it, an ancient fold mountain belt (the Great Dividing Range along the east coast), and a flat platform-like area in-between composed of crystalline or folded rocks overlaid by flat-lying or only gently deformed sediments.

Millions of years of **erosion** have scoured Australia's surface features. One notable exception to Australia's flat topography is the Great Dividing Range stretching 1,200 mi (1,931 km) along Australia's east coast. The Great Dividing Range was thrust up by geological folding like the Appalachian Mountains in the eastern United States. The mountains are superimposed on larger geological structures including the Tasman and Newcastle geosynclines, troughs of older rocks upon which thick layers of sediment have been deposited. Those sediments in turn have been transformed by folding as well as magmatic and volcanic forces.

Twice, during a 125 million year period beginning 400 million years ago, the geosynclines were compressed, forming mountains and initiating volcanoes. Volcanic activity recurred along the Great Dividing Range 20–25 million years ago during the **Miocene Epoch** when early apes evolved as well as seals, dolphins, sunflowers, and bears. However, over millions of years the volcanic cones from this epoch have been stripped down by erosion. Still, volcanic activity persisted in South Australia until less than a million years ago. In Queensland, near Brisbane in the south and Cairns in the north of the state, the Great Dividing Range hugs the coast, creating beautiful Riviera-like vistas.

East of the Great Dividing Range, along Australia's narrow eastern coastal basin are its two largest cities, Sydney and Melbourne, as well as the capital, Canberra. The Dividing Range tends to trap moisture from easterly **weather** fronts originating in the Pacific Ocean. **Rivers** and streams also course the Range. West of the Range the landscape becomes increasingly forbidding and the weather hot and dry.

Although unrelated to geological forces, the world's largest coral formation, the **Great Barrier Reef** stretches for 1,245 mi (2,003 km) along Australia's northeast coast. Most of Australia is referred to as outback—desert and semi-desert flatness, broken only by scrub, salt **lakes** which are actually dry lakebeds most of the year, and a few spectacular **sandstone** proturburances like Uluru (also known as Ayers Rock) and the Olgas (Kata Tjuta).

In 1991, geologists discovered a subterranean electrical current in Australia, the longest in the world, which passes through more than 3,700 mi (6,000 km) across the Australian outback. The current is conducted by **sedimentary rocks** in a long horseshoe arc that skirts a huge mass of older igneous and **metamorphic rock** comprising most of the Northern Territory. It begins at Broome in Western Australia near the Timor Sea and then dips south across South Australia before curling northward through western Queensland where it terminates in the Gulf of Carpenteria.

A side branch runs from Birdsville in South Australia near the Flinders Ranges into Spencer Gulf near Adelaide. Geologists say the current is induced by the Earth's ever-changing **magnetic field** and that it runs along fracture zones in sedimentary basins that were formed as the Earth's ancient plates collided. Although the fracture zones contain alkaline fluids that are good conductors of **electricity**, the current is weak and cannot even light a lamp. Geologists say the current might provide clues to deposits of oil and gas and help explain the geological origins of the Australian continent.

Australian topography is also punctuated by starkly beautiful mountain ranges in the middle of the continent like the McDonnell and Musgrave Ranges, north and south respectively of Uluru (Ayers Rock). Uluru, the most sacred site in the country for Australia's aborigines, is a sandstone monolith of which two-thirds is believed to be below the surface. Ayers Rock is about 2.2 mi (3.5 km) long and 1,131 ft (339 m) high. Also in the center of the country, near Alice Springs, are the Henbury Meteorite craters, one of the largest clusters of meteorite craters in the world. The largest of these depressions, formed by the impact of an extraterrestrial rock, is about 591 ft (177 m) long and 49 ft (15 m) deep.

The continent's oldest rocks are in the Western Australian shield in southwest Australia. The basement (underlying) rocks in this area have not been folded since the **Archean** eon over three billion years ago, when the planet was still very young. The nucleus of this shield (called the Yilgarn craton) comprising 230,000 sq mi (59,570,000 ha), consists mostly of **granite** with belts of metamorphic rock like greenstones, rich in economic mineral deposits as well as intrusions of formerly molten rock.

The Yilgarn craton does not quite extend to the coast of Western Australia. It is bounded on the west by the Darling Fault near Perth. To the south and east the Frazer Fault sets off the craton from somewhat younger rocks that were metamorphosed between 2.5 billion and two billion years ago. Both fault lines are 600 mi (960 km) long and are considered major structures on the continent.

Along the north coast of Western Australia near Port Hedland is another nucleus of ancient rocks, the Pilbara Craton. The Pilbara craton is composed of granites over three billion years old as well as volcanic, greenstone, and sedimentary rocks. The Hammersley Range just south of the

Pilbara Craton is estimated to contain billions of tons of **iron** ore reserves.

Other ancient rock masses in Australia are the Arunta Complex north of Alice Springs in the center of Australia which dates to 2.25 billion years ago. The MacArthur Basin, southwest of the Gulf of Carpenteria in the Northern Territory is a belt of sedimentary rocks that are between 1.8 billion and 1.5 billion years old.

The Musgrave block near the continent's center, a component of the Adelaidian geosyncline, was formed by the repeated intrusion of molten rocks between 1.4 billion to one billion years ago during the **Proterozoic Era** when algae, jellyfish, and worms first arose. At the same time, the rocks that underlay the Adelaidian geosyncline were downwarped by geological pressures, with sediments building up through mid-Cambrian times (about 535 million years ago) when the area was inundated 400 mi (640 km) by the sea inland of the present coastline.

The rocks of the Adelaidian geosyncline are as thick as 10 mi (16 km) with sediments that have been extensively folded and subjected to faulting during late **Precambrian** and early Paleozoic times (about 600 million to 500 million years ago). Some of the rocks of the Adelaidian geosyncline, however, are unaltered. These strata show evidence of a major glacial period around 740 million years ago and contain some of the continent's richest, most diverse fossil records of soft-bodied animals.

This **glaciation** was one manifestation of global cooling that caused glacial episodes on other continents. Geologists say this Precambrian glacial episode was probably one of coldest, most extensive cooling periods in Earth history. They also consider the Adelaide geosyncline to be the precursor of another downwarp related to the most extensive folded belts on the continent, namely the Tasman geosyncline along Australia's east flank.

Victoria is also characterized by a belt of old rocks upon which sediments have been deposited called the Lachlan geosyncline. Marine rocks were deposited in quiet **water** to great thicknesses in Victoria, forming black shales. Some of the sediment was built up by mud-laden currents from higher areas on the sea floor. These current-borne sediments have produced muddy sandstones called graywackes.

At the end of the Ordovician and early Silurian Periods (about 425 million years ago) there was widespread folding of the Lachlan geosyncline called the Benambran **orogeny**. The folding was accompanied by granite intrusions and is thought to be responsible for the composition and texture of the rocks of the Snowy Mountains in Victoria, including Mt. Kosciusko, Australia's tallest peak at 7,310 ft (2,193 m).

In eastern Australia, **Paleozoic Era** volcanic activity built up much of the rock strata. Mountain glaciation during the late Carboniferous period when insects, amphibians, and early reptiles first evolved also transformed the landscape. Mountain building in eastern Australia culminated during the middle and later **Permian Period** (about 250 million years ago) when a huge mass of **magma** (underground molten rock) was emplaced in older rocks in the New England area of northeastern New South Wales. This huge mass, or **batholith**, caused extensive folding to the west and ended the **sedimentation** phase of the Tasman geosyncline. It was also the last major episode of orogeny (mountain building) on the continent.

In parts of Western Australia, particularly the Carnarvon Basin at the mouth of the Gascoyne River, glacial sediments are as thick as 3 mi (5 km). Western Australia, particularly along the coast, has been inundated repeatedly by the sea and has been described by geologists as a mobile shelf area. This is reflected in the alternating strata of deposited marine and non-marine layers.

In the center of Australia is a large sedimentary basin or depression spanning 450 mi (720 km) from east to west and 160 mi (256 km) north to south at its widest point. Sedimentary rocks of all varieties can be found in the basin rocks which erosion shaped into spectacular scenery including Ayres Rock and Mt. Olga. These deposits are mostly of Precambrian age (over 570 million years old), while sediment along the present-day coastline including those in the Eucla Basin off the Great Australian Bight are less than 70 million years old. North of the Eucla Basin is the Nullarbor (meaning treeless) Plain which contains many unexplored **limestone** caves.

Dominating interior southern Queensland is the Great **Artesian** Basin, which features non-marine sands built up during the **Jurassic Period** (190 million to 130 million years ago), sands which contain much of the basin's artesian water. Thousands of holes have been bored in the Great Artesian Basin to extract the water resources underneath but the salt content of water from the basin is relatively high and the water supplies have been used for livestock only.

The Sydney basin formed over the folded rocks of the Tasman geosyncline and is also considered to be an extension of the Great Artesian Basins. Composed of sediments from the Permian and Triassic Periods (290 million to 190 million years old) it extends south and eastward along the **continental shelf**. The sandstone cliffs around Sydney Harbor, often exploited for building stones, date from Triassic sediments.

Minerals in Australia have had a tremendous impact on the country's human history and patterns of settlement. Alluvial gold (gold sediments deposited by rivers and streams) spurred several gold fevers and set the stage for Australia's present demographic patterns. During the post-World War II period there has been almost a continuous run of mineral discoveries, including gold, bauxite, iron, and manganese reserves as well as opals, sapphires, and other precious stones.

It is estimated that Australia has 24 billion tons (22 billion tones) of **coal** reserves, over one-quarter of which (7 billion tons/6 billion tones) is anthracite or black coal deposited in Permian sediments in the Sydney Basin of New South Wales and in Queensland. Brown coal suitable for electricity production in found in Victoria. Australia meets its domestic coal consumption needs with its own reserves and exports the surplus.

Australia supplies much of its oil consumption needs domestically. The first Australian oil discoveries were in southern Queensland near Moonie. Australian oil production now amounts to about 25 million barrels per year and includes pumping from oil fields off northwestern Australia near Barrow Island, Mereenie in the southern Northern Territory, and fields in the Bass Strait. The Barrow Islands, Mereenie, and Bass Strait fields are also sites of **natural gas** production.

Australia has rich deposits of uranium ore, which is refined for use for fuel for the nuclear power industry. Western Queensland, near Mount Isa and Cloncurry contains three billion tons (2.7 billion tones) of uranium ore reserves. There are also uranium deposits in Arnhem Land in far northern Australia, as well as in Queensland and Victoria.

Australia is also extremely rich in zinc reserves, the principal sources for which are Mt. Isa and Mt. Morgan in Queensland. The Northern Territory also has **lead** and zinc mines as well as vast reserves of bauxite (**aluminum** ore), namely at Weipa on the Gulf of Carpenteria and at Gove in Arnhem Land.

Gold production in Australia has declined from a peak production of four million fine ounces in 1904 to several hundred thousand fine ounces. Most gold is extracted from the Kalgoorlie-Norseman area of Western Australia. The continent is also well known for its precious stones, particularly white and black opals from South Australia and western New South Wales. There are sapphires and topaz in Queensland and in the New England District of northeastern New South Wales.

Because of its aridity, Australia suffers from leached, sandy, and salty soils. The continent's largely arid land and marginal water resources represent challenges for conservation and prudent environmental management. One challenge is to maximize the use of these resources for human beings while preserving ecosystems for animal and plant life.

See also Beach and shoreline dynamics; Continental drift theory; Desert and desertification; Earth (planet); Industrial minerals; Plate tectonics; Weathering and weathering series

AVALANCHE

An avalanche is a rapid downslope movement of some combination of **rock**, **regolith**, snow, slush, and **ice**. The movement can occur by any combination of sliding, falling, and rolling of pieces within the avalanche mass, but is generally very rapid. Avalanche velocities can reach tens to hundreds of kilometers per hour.

This avalanche in the Swiss ski resort of Evolene left at least two dead and more than a dozen missing. © *AFP/Corbis Bettman. Reproduced by permission.*

The term avalanche is generally associated with snow and ice. In its most general form, however, it can refer to the cascading of **sand** grains down the leeward face of a dune or the rapid downslope movement of largely disaggregated rock without snow or ice. Rock avalanches, for example, are very rapid and **catastrophic mass movements** of **bedrock** that has been broken into innumerable pieces either before or during movement.

Snow avalanches, hereafter referred to simply as avalanches, are classified according to whether they move across existing snow layers (surface avalanche) or the ground (ground avalanche), whether they are dry or wet, whether they move through the air or over ground and snow, and whether they consist of loose snow or intact slabs. Like landslides, avalanches begin when the weight of snow above some potential sliding surface exceeds the shear strength along that surface. In many cases, sliding occurs along a former snow surface that is quickly buried by new snow during a storm. The **physics** of slip surface formation, however, are more complicated for avalanches than most landslides because the snow and ice in an avalanche prone slope are near their **melting** points. Thus, phase transitions and metamorphosis of snow and ice **crystals** can alter the strength of snow and ice slopes in a way that does not occur in **soil** or rock slopes. Melting can also trigger avalanches. Although it is not proven that loud noises such as shouting can trigger avalanches, the vibrations caused by explosives can do so—and explosives are often used to deliberately trigger avalanches under controlled conditions as a safety measure.

The aftermath of an avalanche is an avalanche track or chute, which is commonly marked by bent or broken trees and significant amounts of **erosion**. The track can be either a channel-like or open feature. The rock and debris carried by an avalanche can be deposited as an avalanche cone when the avalanche comes to rest, and the rock debris deposited at the base of a cliff or other steep slope by an avalanche is known as avalanche talus.

See also Catastrophic mass movements; Freezing and melting; Ice; Landslide; Mass movement; Mass wasting; Phase state changes

AVIATION PHYSIOLOGY

Aviation physiology deals with the physiological challenges encountered by pilots and passengers when subjected to the environment and stresses of flight.

Human physiology is evolutionarily adapted to be efficient up to about 12,000 feet above sea level (the limit of the physiological efficiency zone). Outside of this zone, physiological compensatory mechanisms may not be able to cope with the stresses of altitude.

Military pilots undergo a series of exercises in high altitude simulating hypobaric (low pressure) chambers to simulate the early stages of hypoxia (**oxygen** depletion in the body). The tests provide evidence of the rapid deterioration of motor skills and critical thinking ability when pilots undertake flight above 10,000 feet above sea level without the use of supplemental oxygen. Hypoxia can also **lead** to hyperventilation as the body attempts to increase breathing rates.

Altitude-induced decompression sickness is another common side effect of high altitude exposure in unpressurized or inadequately pressurized aircraft. Although the percentage of oxygen in the atmosphere remains about 21% (the other 79% of the atmosphere is composed of nitrogen and a small amount of trace gases), there is a rapid decline in **atmospheric pressure** with increasing altitude. Essentially, the decline in pressure reflects the decrease in the absolute number of molecules present in any given volume of air.

Pressure changes can adversely affect the middle ear, sinuses, teeth, and gastrointestinal tract. Any sinus block (barosinusitis) or occlusions that inhibit equalization of external pressure with pressure within the ear usually results in severe pain. In severe cases, rupture of the tympanic membrane may occur. Maxillary sinusitis may produce pain that is improperly perceived as a toothache. This is an example of referred pain. Pain related to trapped gas in the tooth itself (barondontalgia) may also occur.

Ear block (barotitis media) also causes loss of hearing acuity (the ability to hear sounds across a broad range of pitch and volume). Pilots and passengers may use the Valsalva maneuver (closing the mouth and pinching the nose while attempting to exhale) to counteract the effects of **water** pressure on the Eustachian tubes and to eliminate pressure problems associated with the middle ear. When subjected to pressure, the tubes may collapse or fail to open unless pressurized. Eustachian tubes connect the corresponding left and right middle ears to the back of the nose and throat, and function to allow the equalization of pressure in the middle ear air cavity with the outside (ambient) air pressure. The degree of Eustachian tube pressurization can be roughly regulated by the intensity of abdominal, thoracic, neck, and mouth muscular contractions used to increase pressure in the closed airway.

Rapid changes in altitude allow trapped gases to cause pain in joints in much the same way—although to a far lesser extent—that the bends causes pain in scuba divers. Lowered outside atmospheric pressure creates a strong pressure gradient that permits dissolved nitrogen and other dissolved or “trapped” gases within the body to attempt to “bubble off” or leave the blood and tissues in an attempt to move down the concentration gradient toward a region of lower pressure.

Spatial disorientation trainers demonstrate the disorientation and loss of balance (vestibular disorientation) that can be associated with flight at night—or in clouds—where the pilot losses the horizon as a visual reference frame. Balance and the sense of turning depend upon the ability to discriminate changes in the motion of fluids within the semicircular canals of the ear. When turns are gradual, the changes become imperceptible because the fluids are moving at a constant velocity. Accordingly, without visual reference, pilots can often enter into steep turns or dives without noticing any changes. Spatial disorientation chambers allows pilots to learn to “trust their instruments” as opposed to their error-prone sense of balance when flying in IFR (Instrument Flight Rules) conditions.

In addition to vestibular disorientation, spatial disorientation can also lead to motion sickness.

Because of the highly repetitive nature of the active pilot scan of instruments, fatigue is a chronic problem for pilots. Fatigue combined with low oxygen pressures may induce strong and disorienting visual illusions.

Although not often experienced in general aviation, military pilots operate at high speeds and undertake maneuvers that subject them to high “g” (gravitational) forces. In a vertical climb, the increased g forces (called positive “g” forces because they push down on the body) tend to force blood out of the circle of Willis supplying arterial blood to the brain. The loss of oxygenated blood to the brain eventually causes pilots to lose their field of peripheral vision. Higher forces cause “blackouts” or temporary periods of unconsciousness. Pilots can use special abdominal exercises and “g” suits (essentially adjustable air bladders that can constrict the legs and abdomen) to help maintain blood in the upper half of the body when subjected to positive “g” forces.

In a dive, a pilot experiences increased upward “g” forces (termed negative “g” forces) that force blood into the arterial circle of Willis and cerebral tissue. The pilot tends to experience a red out. Increased arterial pressures in the brain can lead to stroke. Although pilots have the equipment and physical stamina to sustain many positive “g” forces (routinely as high as five to nine times the normal force of **gravity**) pilots experience red out at about 2–3 negative “g’s.” For this reason, maneuvers such as loop, rolls, and turns are designed to minimize pilot exposure to negative “g” forces.

See also Aerodynamics; Atmospheric composition and structure

AXIS • *see* POLAR AXIS AND TILT

B

BALLARD, ROBERT DUANE (1942-)

American oceanographer and archaeologist

Robert Ballard has participated in over 100 deep-sea expeditions during his career. Ballard is perhaps most well known for leading the 1985 French-American expedition that discovered the wreckage of the RMS *Titanic*. However, Ballard has made many great contributions to the fields of **oceanography**, marine **geology**, and underwater archaeology. He is a pioneer in the use of underwater submersibles in the location and survey of deep-water subjects.

Ballard was born in Wichita, Kansas, but his family soon moved to San Diego, California. He developed a lifelong love of the ocean as a child. When he was a teenager, he traded studying creatures in tidal pools for SCUBA lessons. Ballard decided to pursue ocean research as a career when he entered college. He attended the University of California, earning dual undergraduate degrees in geology and **chemistry** in 1965. He trained dolphins for a local marine theme park while pursuing postgraduate studies at the University of Hawaii. Ballard was a member of the Army Reserve Officer Training Corps, but petitioned for transfer to the Navy in 1967. The U.S. Navy granted his request and assigned him to the Deep Submergence Laboratory at Woods Hole, Massachusetts. He completed his graduate studies at the University of Rhode Island, receiving a Ph.D. in geophysics and marine geology in 1974.

The first major research expedition of Ballard's career was the first manned exploration of the Mid-Atlantic Ridge, a large underwater mountain range in the Atlantic Ocean, in 1973–1974. The survey mapped some of the most varied terrain of the ocean floor. In 1977, Ballard was a member of research team that used small submersibles to explore the waters near the Galapagos Islands. Dr. Ballard and his crew observed ecosystems that developed around underwater hot **springs**. Two years later, off the coast of Baja California, Ballard found underwater volcanoes that ejected hot, mineral rich fluids. Ballard and his team studied the effects of these vents on deep marine life and ocean **water** chemistry.

In 1985, Ballard and his team turned their attention to finding one of the most famous shipwrecks, the RMS *Titanic*, a British luxury steamship that sank in the North Atlantic in 1912. Experienced using small manned submersibles, such as ALVIN, Ballard designed other survey apparatus, such as the ARGO-JASON, a remote controlled deep-sea imaging system. In order to gain access to the most sophisticated equipment for his search for the *Titanic*, Ballard was first assigned to conduct deep-sea reconnaissance work for the United States Navy, finding and evaluating the site of a sunken U.S. nuclear submarine. After completing his work for the Navy, Ballard used the remaining expedition time for his join French and American research team to locate the *Titanic*. The team located the wreckage of the British steamer just days before their voyage was to end. Ballard used the submersible JASON to photograph the site. In addition, Ballard and his team designed a small accessory robotic device, named JASON Jr., which could explore the inside of the ship by remote control. Using this array of sophisticated diving equipment, and small submersibles, Ballard also found the wrecks of the USS *Yorktown*, the German battleship *Bismarck*, and part of the lost fleet of Guadalcanal. He also led an expedition to photograph and explore the British luxury liner, *Lusitania*.

Remaining on the cutting edge of under-sea research and exploration, Ballard left Woods Hole in 1997 to pursue career interests in underwater archaeology. Combining his knowledge of deep-water oceanography, and a passion for historic preservation, Ballard accepted a post to head the Institute for Exploration in Mystic, Connecticut. That year, Ballard, using the Navy's nuclear research submarine, NR-1, explored a complex of 2,000 year-old shipwrecks in the Mediterranean Sea. Because of the depth at which the wrecks settled, the site remained perfectly preserved. In 2000, Ballard was named National Geographic's Explorer-in-Residence.

See also Deep sea exploration

BANDED IRON FORMATIONS

Banded **iron** formations (BIFs) are chemically precipitated **sedimentary rocks**. They are composed of alternating thin (millimeter to centimeter scale) red, yellow, or cream colored layers of **chert** or jasper and black to dark gray iron oxides (predominantly magnetite and hematite), and/or iron carbonate (siderite) layers. Banded iron formations have greater than 15% sedimentary iron content. Banded iron formations are of economic interest as they host the world's largest iron ore deposits and many gold deposits.

Algoma-type banded iron formations were deposited as chemical sediments along with other sedimentary rocks (such as greywacke and shale) and volcanics in and adjacent to volcanic arcs and spreading centers. Iron and silica were derived from hydrothermal sources associated with volcanic centres. Algoma-type iron formations are common in **Archean** greenstone belts, but may also occur in younger rocks.

Lake Superior-type banded iron formations were chemically precipitated on marine continental shelves and in shallow basins. They are commonly interlayered with other sedimentary or volcanic rocks such as shale and **tuff**. Most Lake Superior-type banded iron formations formed during the Paleoproterozoic, between 2.5 and 1.8 billion years ago. Prior to this, Earth's primitive atmosphere and **oceans** had little or no free **oxygen** to react with iron, resulting in high iron concentrations in seawater. Iron may have been derived from the **weathering** of iron-rich rocks, transported to the sea as water-soluble Fe^{+2}. Alternatively, or in addition, both iron and silica may have been derived from submarine magmatic and hydrothermal activity. Under calm, shallow marine conditions, the iron in seawater combined with oxygen released during photosynthesis by Cyanobacteria (primitive blue-green algae, which began to proliferate in near-surface waters in the Paleoproterozoic) to precipitate magnetite (Fe_3O_4), which sank to the sea floor, forming an iron-rich layer.

It has been proposed that during periods when there was too great a concentration of oxygen (in excess of that required to bond with the iron in the seawater) due to an abundance of blue-green algae, the blue-green algae would have been reduced in numbers or destroyed. A temporary decrease in the oxygen content of the seawater then eventuated. When magnetite formation was impeded due to a reduction in the amount of oxygen in seawater, a layer of silica and/or carbonate was deposited. With subsequent reestablishment of Cyanobacteria (and thus renewed production of oxygen), **precipitation** of iron recommenced. Repetitions of this cycle resulted in deposition of alternating iron-rich and silica- or carbonate-rich layers. Variations in the amount of iron in seawater, such as due to changes in volcanic activity, may have also led to rhythmic layering. The large lateral extent of individual thin layers implies changes in oxygen or iron content of seawater to be regional, and necessitates calm depositional conditions. Iron and silica-rich layers, originally deposited as **amorphous** gels, subsequently lithified to form banded iron formations. The distribution of Lake Superior-type banded iron formations of the same age range in **Precambrian** cratons worldwide suggests that they record a period of global change in the oxygen content of the earth's atmosphere and oceans. Also, the worldwide abundance of large, calm, shallow platforms where cyanobacterial mats flourished and banded iron formations were deposited may imply a global rise in sea level.

Primary carbonate in banded iron formations may be replaced by silica during diagenesis or deformation. The pronounced layering in banded iron formations may be further accentuated during deformation by pressure solution; silica and/or carbonate are dissolved and iron oxides such as hematite may crystallize along pressure solution (stylolite) surfaces. Banded iron formations are highly anisotropic rocks. When shortened parallel to their layering, they deform to form angular to rounded **folds**, kink bands, and box folds. Folds in banded iron formations are typically doubly plunging and conical. Banded iron formations may interact with hot fluids channeled along faults and more permeable, interbedded horizons such as **dolomite** during deformation. This may remove large volumes of silica, resulting in concentration of iron. Iron, in the form of microplaty hematite can also crystallize in structurally controlled sites such as fold hinges and along detachment faults. If there is sufficient enrichment, an iron ore body is formed. Iron may also be leached, redeposited and concentrated during weathering to form supergene iron ore deposits. Fibrous growth of **quartz** and **minerals** such as crocidolite (an amphibole, also known as asbestiform riebeckite) commonly occurs in banded iron formations during deformation due to dilation between layers, especially in fold hinges. Replacement of crocidolite by silica produces shimmering brown, yellow and orange "tiger-eye," which is utilized in jewelry and for ornamental use.

See also Industrial minerals

BARCHAN DUNES • *see* DUNES

BAROMETER • *see* ATMOSPHERIC PRESSURE

BARRIER ISLANDS

A barrier island is a long, thin, sandy stretch of land, oriented parallel to the mainland coast that protects the coast from the full force of powerful storm waves. Between the barrier island and the mainland is a calm, protected **water** body such as a lagoon or bay. Barrier islands are dynamic systems, constantly on the move, migrating under the influence of changing sea levels, storms, waves, **tides**, and longshore currents. In the United States, barrier islands occur offshore where gently sloping sandy coastlines, as opposed to rocky coastlines, exist. Consequently, most barrier islands are found along the Gulf Coast and the Atlantic Coast as far north as Long Island, New York. Some of the better known barrier islands include Padre Island of Texas, the world's longest; Florida's Santa Rosa Island, composed of sugar-white **sand**; Cape Hatteras of North Carolina, where the first airplane was flown; and Assateague Island near Maryland, home of wild ponies.

Barrier islands are young in geologic terms. They originated in the **Holocene Epoch**, about 4,000–6,000 years ago. During this time, the rapid rise in sea level, associated with **melting glaciers** from the last **ice** age, slowed significantly. Although the exact mechanisms of barrier island formation aren't fully understood, this slowdown of sea level rise allowed the islands to form.

In order for barrier islands to form, several conditions must be met. First, there must be a source of sand to build the island. This sand may come from coastal deposits or offshore deposits (called shoals); in either case, the sand originated from the **weathering** and **erosion** of **rock** and was transported to the coast by **rivers**. In the United States, much of the sand composing barrier islands along Florida and the East Coast came from the Appalachian Mountains. Next, the **topography** of the coastline must have a broad, gentle slope. From the coastal plains of the mainland to the edge of the **continental shelf**, this condition is met along the Atlantic and Gulf Coasts. Finally, the forces of waves, tides and currents must be strong enough to move the sand, and of these three water movement mechanisms, waves must be the dominant force.

Several explanations for barrier island development have been proposed. According to one theory, coastal sand was transported shoreward as sea level rose, and once sea level stabilized, wave and tidal actions worked the sand into a barrier island. Another possibility is that sand was transported to its present location from shoals. Barrier islands may have formed when low-lying areas of spits, extensions of beaches that protrude into a bay as a result of deposition of sediment carried by longshore currents, were breached by the sea. Finally, barrier islands may have formed from sandy coastal ridges that became isolated from low-lying land and formed islands as sea level rose.

Once formed, barrier islands are not static **landforms**; they are dynamic, with winds and waves constantly reworking and moving the barrier island sand. Changes in sea level also affect these islands. Most scientists agree that sea level has been gradually rising over the last thousand years, and this rise could be accelerating today due to **global warming**. Rising sea level causes existing islands to migrate shoreward.

Barrier islands do not stand alone in a geologic sense. A whole system of islands develops along favorable coastlines. The formation of these islands allows other landforms to develop, each characterized by their dominant sediment type and by the water that helps form them. For example, each barrier island has a shoreline that faces the sea and receives the full force of waves, tides, and currents. This shoreline is often called the beach. The beach zone extends from slightly offshore (subtidal, or underwater) to the high water line. Coarser sands and gravels are deposited here, with finer sands and silts carried farther offshore.

Behind the beach are sand **dunes**. **Wind** and plants (such as sea oats) help form dunes, but occasionally dunes are inundated by high water and may be reworked by storm surges and waves. On wide barrier islands, the landscape behind the foredunes gently rolls as dunes alternate with low-lying swales (marshy wet areas). If the dunes and swales are well developed, distinct parallel lines of dune ridges and swales can be seen from overhead. These differences in topography allow some **soil** to develop and nutrients to accumulate despite the porous, sandy base. Consequently, some barrier islands are host to trees (which are often stunted), bushes, and herbaceous plants. Other narrower or younger barrier islands may be little more than loose sand with few plants.

On the shoreward side of the main body of the island is the back-barrier. Unlike the beach, this zone does not bear the full force of ocean waves. Instead, the back-barrier region consists of a protected shoreline and lagoon, which is more influenced by tides than waves. Occasionally, during storms, water may rush over the island carrying beach and dune sand and deposit the sand in the lagoon. This process, called rolling over, is vital to the existence of barrier islands and is the method by which a barrier island migrates landward. Characteristic sand washover fans in the lagoons are evidence of rolling over. Because the back-barrier region is sheltered, salt marsh, sea grass, and mudflat communities develop. These communities teem with plant and animal life and their muddy or sandy sediments are rich with organic matter.

Finally, barrier islands are characterized by tidal inlets and tidal deltas. Tidal inlets allow water to move into and out of bays and lagoons with rising and falling tides. Tidal inlets also provide a path for high water during storms and hurricanes. As water moves through an inlet, sand is deposited at both ends of the inlet's mouth, forming tidal deltas. Longshore currents may also deposit sand at the **delta**. Eventually the deltas fill in with sand and the inlet closes, only to appear elsewhere on the barrier island, usually at a low-lying spot. The size and shape of the inlet are determined by various factors, including the size of the associated lagoon and the tidal range, or the vertical height between high and low tide for the **area**. A large tidal range promotes the formation of numerous inlets, thereby creating shorter and wider barrier islands referred to as drumsticks. In addition, the larger the lagoon and the greater the tidal range, the deeper and wider the inlet due to the large quantity of water moving from ocean to lagoon and back. Deep, wide inlets occur where the main source of energy shaping the coastal area is tides or tides in conjunction with waves. In contrast, wave-dominated areas form long barrier islands with narrow bays and narrow, shallow inlets.

See also Beach and shoreline dynamics; Gulf of Mexico; Offshore bars; Tropical cyclone; Wave motions

BARRINGER METEOR CRATER

The Barringer Meteor Crater in Arizona was the first recognized terrestrial **impact crater**. The confirmation of a meteor impact (subsequently identified as the **Canyon** Diablo meteorite) at the site proved an important stepping-stone for advances in **geology** and **astronomy**. In solving the mystery surrounding the origin of the Barringer crater, geologists and astronomers made substantial progress in understanding the dynamic interplay of gradual and cataclysmic geologic processes both on Earth and on extra-terrestrial bodies.

Barringer Meteor Crater, Arizona. ***U.S. National Aeronautics and Space Administration (NASA).***

The Barringer Meteorite Crater (originally named Coon Butte or Coon Mountain) rises 150 feet above the floor of the surrounding Arizona **desert**. The impact crater itself is almost a mile wide and 570 feet deep. Among geologists, two competing theories were most often asserted to explain the geologic phenomena. Before the nature of hot spots or plate tectonic theory would have convinced them otherwise, many geologists hypothesized that the crater resulted from volcanic activity. A minority of geologists asserted that the crater must have resulted from a meteor impact.

In the last decade of the nineteenth century, American geologist Grove Karl Gilbert, then the head of the U.S. Geological Survey, set out to determine the origin of the crater. Gilbert assumed that for a meteor to have created such a large crater, it was necessary for it to remain intact through its fiery plunge through the earth's protective atmosphere. Moreover, Gilbert assumed that most of the meteor survived its impact with Earth. Gilbert, therefore, assumed that if a meteor collision was responsible for the crater, substantial pieces of the meteor should still exist and there should be ample and direct physical evidence of the size of the meteor. When upon observation it became apparent that there was no substantial mass inside the crater, Gilbert assumed that the meteor might have been covered with the passage of time. Assuming the meteor to be like other known meteorites and similar in percentage of **iron** composition to the smaller meteors found around the crater, Gilbert looked for magnetic evidence in a effort to find the elusive meteor. Gilbert's repeated tests found no evidence for such a buried mass. After carefully examining the crater, Gilbert concluded that, in the absence of the evidence he assumed would be associated with a meteor impact, the crater had resulted from subterranean activity.

In 1902, Daniel Moreau Barringer, an American entrepreneur and mining engineer, began a study of the Arizona crater and took up the opposing view. After discovering that small meteors made of iron had been found at or near the rim of the crater, Barringer was convinced that only a large iron meteor could be the cause of such a geologic phenomenon. Acting more like a businessman or miner trying to stake a claim, and before doing any studies on the potential masses and energies that would have to be involved in such an impact, Barringer seized the opportunity to form company with the intent of mining the iron from the presumed meteor for commercial profit. Without actually visiting the crater, Barringer formed the Standard Iron Company and sought mining permits.

For nearly the next thirty years, Barringer became the sword and shield of often-rancorous scientific warfare regarding the origin of the crater. In bitter irony, Barringer won the scientific battle, the proof eventually accumulated that the crater resulted from a meteor impact, but lost his financial gamble. In the end, the meteor that caused the impact proved much smaller than hypothesized by either Gilbert or Barringer, and the nature of the impact obliterative. On the heels of these finding in 1929, Barringer died of a heart attack. His lasting legacy was in the attachment of his name to the impact crater.

The debate over the origin of the Great Barringer Meteor Crater came at a time when geology itself was reassessing its methodologies. Within the geologic community there was often vigorous debate over how to interpret geologic data. In particular, debates ranged regarding the scope and extent of **uniformitarianism**. In its simplest form, uniformitarianism asserted only that the laws of **physics** and **chemistry** remained unchanged during the geologic history of the Earth. Debate centered on whether the predominantly dominant gradualism (similar to evolutionary gradualism) of geologic processes was significantly affected by catastrophic events.

Barringer confidently asserted that the Coon Butte crater supported evidence of catastrophic process. Although he argued selective evidence, Barringer turned out to be correct when he asserted that the finely pulverized silica surrounding the crater could have only been created in a process that created instantaneously great pressures. Beyond the absence of volcanic rocks, Barringer argued that there were too many of the iron fragments around the crater to have come from gradually accumulated separate meteor impacts. Moreover, Barringer noticed that instead of defined strata (layers) there was a randomized mixture of the fragments and ejecta (native **rock** presumable thrown out of the crater at the time of impact). Such a random mixture could only have resulted from a cataclysmic impact.

Barringer's cause gained support of mainstream geologists when American geologist George P. Merrill tested rocks taken from the rim and floor of the crater. Merrill concluded that the quartz-like **glass** found in abundance in the presumed eject could only have been created by subjecting the native sands to intense heat. More importantly, Merrill concluded that the absence of sub-surface fusions proved the heat could not have come from below the surface.

The evidence collected by Barringer also influenced astronomers seeking, at that time to explain large, round craters on the **moon**. Once again, the debate moved between those championing extra-terrestrial volcanic activity (gradualism) versus those who favored an impact hypothesis (cataclysm). This outcome of these debates had enormous impact in both geology and astronomy.

One fact that perplexed astronomers was that it appeared that all of the lunar impact craters were generally round. If meteors struck the Moon at varying angles, it was argued, then the craters should have assumed a variety of oblique shapes. Barringer and his 12-year-old son set out to experiment with the formation of such craters by firing bullets into clumps of rock and mud. Regardless of the firing angle, the Barringers demonstrated (and published their results in both popular and scientific magazines) that the resulting craters were substantially round. More definitive proof was subsequently provided in 1924 by calculations of astronomers who determined that forces of impact at astronomical speeds likely resulted in the explosive destruction of the impacting body. Importantly, regardless of the angle of impact, the result of such explosions would leave rounded craters.

The confirmation that a meteor weighing about 300,000 tons (less than a tenth of what Barringer had estimated) and traveling in excess of 35,000 mph at impact could have produced the energy and catastrophic phenomena observed proved a double edge sword for Barringer. In one stroke, his hypothesis that the crater was caused by a meteor impact gained widespread support while, at the same time Barringer's hopes of profitably mining the meteor vaporized like much of the exploded meteor itself.

The scientific debate on the origin of Barringer crater was essentially closed when it was dramatically demonstrated that meteor impacts could impart such large energies far above even the tremendous power of nuclear weapons. In the 1960s, American astronomer and geologist Eugene Shoemaker found distinct similarities between the fused rocks found at Barringer crater and those found at atomic test sites. In addition, unique geologic features termed "shattercones" created by the instantaneous application of tremendous pressure pointed to a tremendous explosion at or above the impact crater. Determinations made by later, more sophisticated dating techniques placed the age of the crater at roughly 50,000 years.

Scientists subsequently understood that massive cataclysmic collisions result in what is now termed **shock metamorphism**. These shock metamorphic effects have been shown to be exclusively associated with meteorite impact craters. No other natural process on earth can account for the observed results.

A great deal of such evidence methodologies derived from the Barringer crater controversy now points to a catastrophic astronomical collision at the end of the **Cretaceous Period** 66 million years ago. The effects of this collision are thought to have precipitated the widespread extinction of large species, including the dinosaurs. The enigmatic Tunguska explosion of 1908, which devastated an vast **area** of Siberian forest, may have been Earth's most recent significant encounter with an impacting object vaporized so as to leave little physical remains beyond the manifest effects of a tremendous explosion.

Methods used to confirm Barringer crater as a meteor impact crater have been used to identify many other impact sites around the world. Once scientists became aware of the tremendous energies involved in astronomical impacts, large terrestrial impacts, often hidden by erosive effects, became a focus of study. With more than 150 such impact sites identified, impacts have taken on an important role in understanding the Earth's geologic history. The accumulated evidence led to a synthesis of gradualism and catastrophic theory. In accord with uniformitarianism, the gradual and inexorable shaping processes taking place over **geologic time** were understood to be punctuated with catastrophic events.

BASALT

Basalt is a **mafic** volcanic **rock** consisting primarily of **plagioclase feldspar** and pyroxene **minerals**. Common accessory minerals can include other pyroxenes, **olivine**, **quartz**, and nepheline. Basalt is the volcanic equivalent of the plutonic rock gabbro, and as such has a low silica content (48%–52%). Like other volcanic rocks, basalt cools quickly after it erupts and therefore generally contains less than 50% visible **crystals** floating in a matrix of **glass** or microscopic crystals. Pillow basalt, consisting of lobes of **lava** emplaced and solidified on top of each other, is the result of undersea eruptions such as those along divergent oceanic plate boundaries. Basalt is also known to occur on the **moon**.

Because of its low silica content, which translates into a high **melting** point and low viscosity, basaltic lava erupts at a higher **temperature** (2,012–2,192°F; 1,100–1,250°C) and flows more easily across low slopes that do more **silicic** lava types. Under some conditions, basaltic lava can flow more than 12.5 miles (20 km) from the point of eruption. The low viscosity of molten basalt also means that dissolved volcanic gasses can escape relatively easily as the **magma** travels to the surface and confining pressure is reduced. Thus, basalt eruptions tend to be quiet and effusive (as typified by Hawaiian volcanoes) as compared to the explosive eruptions often associated with more viscous and silica-rich lava (as typified by Mount St. Helens). Lava fountains can, however, reach heights of several hundred meters during basaltic eruptions.

Lava flows that solidify with a smooth or ropy surface are often described using the Hawaiian term *pahoehoe*, whereas those which solidify with a jagged or blocky surface are described by the Hawaiian term *aa*. The former is pronounced "pa-hoy-hoy" and the latter is pronounced "ah-ah."

Another characteristic of many basalt flows is the presence of polygonal columnar joints, which are understood to form by contraction of the lava as it cools. The result is a system of nearly vertical joints that form a polygonal pattern when viewed from above and break the rock into slender prismatic columns.

See also Divergent plate boundary; Extrusive cooling; Joint and jointing; Rate factors in geologic processes; Rifting and rift valleys; Sea-floor spreading

Devil's Tower National Monument in Wyoming is a column of basalt that has resisted weathering, unlike the less-resistent rock that once surrounded it. © *Dave G. Houser/Corbis. Reproduced by permission.*

BASIN AND RANGE TOPOGRAPHY

Basin and range **topography** is characterized by tilted fault blocks forming sub-parallel mountain ranges and intervening sediment-filled basins. These elements are typical of the basin and range physiographic topography in the western United States. This province is bounded on the east by the Colorado Plateau, the Columbia and Snake River Plateaus to the north, the Sierra Nevada to the west, and extends southward through eastern California and southern Arizona into northern Mexico. Nearly the entire state of Nevada and western Utah exhibit features distinctive to basin and range topography.

Within the basin and range province, steep mountain ranges are bounded by normal faults, with ground motion along the faults resulting in the relative uplift of the mountains and dropping of the valleys. The longitudinal mountain ranges lie generally parallel to each other and trend northward, leading one early geologist to compare a map view of the ranges within the province to a group of caterpillars crawling slowly north. The bare mountains are cut by numerous drainages that carry the products of **weathering** into the basins below. Sediment in the resultant alluvial fans eventually fills the intermontane basin. In some cases, as much as 10,000 feet of **sand**, gravel, and **clay** has accumulated. Ultimately, these relatively featureless alluvial slopes conceal the majority of the fault-block mountains and the faults from which they were formed.

The fundamental structural element of the region is the ever-present north-south trending normal fault. The presence of the normal faults is indicative of tensional stress over the region oriented in an east-west direction. This stress has produced dramatic crustal extension in this same direction, thus allowing the valley blocks to drop between the bounding normal faults as the ranges were stretched apart. Directly related to the tensional stress is the general tectonic uplift of the entire region than began approximately 15 million years ago.

Although geologists have an understanding of the mechanisms by which the basin and range formed, the thinner **crust** and higher heat flow of the **area** present strong evidence that conditions within the upper mantle are responsible. The most common explanation for these conditions is related to the subduction of a crustal plate producing chemical and physical changes within the mantle. Upwelling of heated, lower-density material caused the crust to bow upward. This, in turn, produced the high heat flow, uplift, crustal thin-

Titcomb Basin, Wind River Range. © ***Richard Hamilton Smith/Corbis. Reproduced by permission.***

ning, and regional extension observed in basin and range topography.

See also Alluvial system; Faults and fractures; Plate tectonics

BATHOLITH

Batholiths are large bodies of intrusive igneous **rock**. Formed when **magma** cools and crystallizes beneath Earth's surface, batholiths are the largest type of **pluton**. By definition, a batholith must cover at least 39 mi^2 (100 km^2), although most are even larger. Many batholiths cover hundreds to thousands of square miles. The Idaho batholith, for example, has a surface **area** of over 15,500 mi^2 (40,000 km^2).

Batholiths are generally not comprised of one continuous magmatic intrusion; rather, they are produced by repeated intrusions, and most batholiths are made up of multiple individual plutons. Intruded rock cools and solidifies, later to be exposed at the surface through **erosion**. Because they cool beneath Earth's surface, batholiths have a coarse grained texture, and most are granitic in composition.

Usually associated with mountain building, batholiths are often emplaced near continental margins during periods of subduction. As the subducting slab descends, it begins to melt, and multiple plutons are intruded beneath the continent to form the core of the volcanic arc. The Sierra Nevada Mountains, for example, are comprised of a granitic batholith, which is made up of hundreds of individual plutons intruded over a period of several million years. Emplacement of the Sierra Nevada batholith occurred during a mountain building episode known as the Nevadan **orogeny**, initiated during the Jurassic. Uplift and erosion of the area later exposed the batholith, which now forms the spine of the famous mountains.

The Sierra Nevada batholith not only forms a major mountain chain, but also was responsible for driving the California gold rush. Precious **minerals** including gold are commonly associated with granitic batholiths. As mineral-rich solutions move along cracks in the rock body, gold, copper, and other minerals, especially **quartz**, precipitate out. Gold may be mined from deposits known as quartz veins that form along the fractures. The Mother Lode in the Sierra Nevada is possibly the most famous of such deposits.

Determining the mechanism for batholith emplacement has been a topic of much debate. When gigantic batholiths are intruded, the surrounding rock, known as the **country rock**, must somehow make room for the intrusion. Several models have been suggested, but most geologists now agree that a mechanism known as forceful injection is probably responsible for emplacement. Apparently, as the body of magma rises, it deforms the country rock, pushing it out of the way.

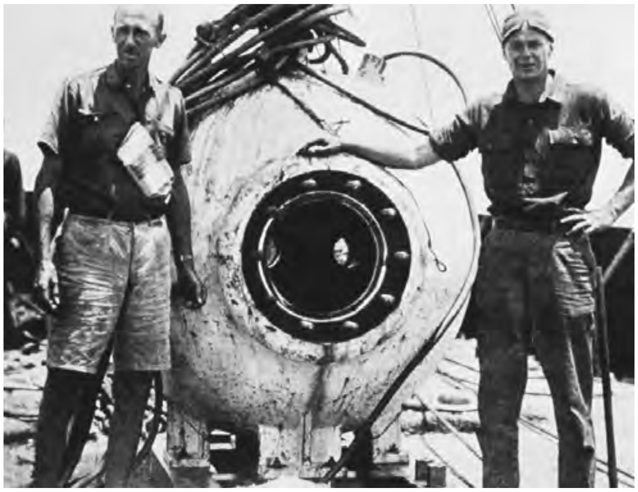
See also Intrusive cooling; Mineral deposits; Pluton and plutonic bodies

BATHYMETRIC MAPPING

Bathymetric mapping refers to construction of ocean and sea maps—bathymetric maps (BM). Bathymetric maps represent the ocean (sea) depth depending on geographical coordinates, just as topographic maps represent the altitude of Earth's surface in different geographic points.

The most popular kind of bathymetric maps is one on which lines of equal depths (isobaths) are represented. Like geographical maps of the surface of Earth, bathymetric maps are constructed in definite **cartography projection**. Mercator projection is used perhaps more often in constructing bathymetric maps, and has been used for a long time in constructing sea charts that are used for sailing in all latitudes except Polar ones.

The creation of a bathymetric map of a given region depends above all on the amount of depth measurement data for that region. Before the invention of the echosounder in 1920's, ocean (sea) depth could be measured only by **lead**. Such measurements were quite rare; these measurements were made only in isolated points, and creation of bathymetric map-



William Beebe and Otis Barton posing with their invention, the bathysphere. © *Ralph White/Corbis. Reproduced by permission.*

ping was practically impossible. Thus, the structure of the ocean floor was virtually unknown. It should be noted, for example, that the most important structure in Atlantic, the Middle-Atlantic ridge, was discovered and began to be investigated only after World War II. Another important factor for creating bathymetric mapping is determining geographical coordinates of the point where the depth measurement is made. It is evident that when these determinations are more precise, then the maps are better. Today, the **GPS** (Global Positioning System) is used for determining the coordinates of the measurement points.

When constructing topographic maps of land, one can always measure the altitude of any point of the surface precisely. However, when constructing a bathymetric map, it is practically impossible to determine the exact depth of any point of the bottom of the sea. Obviously, bathymetric maps are more precise when more data of depth measurement per surface **area** unit in the given region are available. Nowadays, the most precise and detailed bathymetric maps result from using data from multibeam echosounding. The multibeam echosounder is a special kind of echosounder, which is located on board the vessel and measures the depth simultaneously in several points of the bottom. These points are located on the straight line perpendicular to the vessel track. These points themselves are determined by the reflection of several acoustical pulses (beams) directed from one point at different angles to the vertical. The determination of depth in this method is performed regularly within periods of several seconds during the vessel motion. The measurement data are stored in a computer and using them the map of isobath of narrow bottom stripe can be represented periodically, or these data can be represented on a monitor.

It should be noted that in addition to the multibeam echosounder, other devices that measure depths simultaneously in several points of the ocean bottom have been developed, but all of them are based on the reflection of sound signals from the bottom.

If there is a lot of measurement data (more precisely this means that the average amount of measurement data per surface area unit is relatively big, and the measurement points themselves are located uniformly on the surface investigated), then computer methods of isobath construction are used. In this case, two stages of the work are executed. First, using the measurement data obtained in arbitrary points of the surface, the values of the depth in knots of regular grid are calculated (sometimes this stage is known as digital surface model construction). Then using these grid values, coordinates of different isobaths are determined (grid values are used also for other forms of bathometric mapping representations, 3-D views, for example). There are many algorithms of digital model creation, such as the least mean square method, and so-called Kriging method, as well as algorithms of constructing an isobath of its own using depth grid values. To construct a precise map of the region it is necessary to perform echosounding surveying on it in such a manner that map stripes, obtained in different vessel tracks, would be as close to each other as possible, or even overlap. After performing such surveying, all data are joined together, and the map of the entire region is constructed.

It should be noted that presently, only a small part of Earth’s ocean bottom (several percent) is covered by such precise measurements. In some places, little data is available in a study area, obtained by one beam echosounder, or there is no data at all. In these cases, scientists try to use results of other geophysical measurements, first of all gravimetric measurements, to determine ocean depth. For example, methods of determination of ocean bottom **topography** using **satellite** altimetry or marine gravimetry data are useful. Even with using otherwise accurate satellite technology, indirect geophysical methods for determining the ocean bottom depth can always contain a mistake. Earth and its surface are very complex formations, so the precise value of the ocean depth in a given point should be determined if necessary only by direct measurement.

In the case when depth measurement data are small in numbers for a given region, indirect methods are used in constructing bathymetric mapping, such as geomorphology analysis, for example. Scientists also take into account geological considerations and even human intuition, which can at times be useful.

Several international organizations are currently working on bathymetric mapping of the world’s **oceans**. The *General Bathymetric Chart of the Oceans* (GEBCO, in the scale 1:5000000), which may be considered a reference map, is one example. In this map, data of many regional bathymetric maps are collected, taking into account the different methods of their construction. There is also a digital version of this map (on CD), where files are represented in different formats, and in ASCII codes in particular, and where isobaths are represented in the so-called vector format.

Bathymetric mapping is finding increasing scientific and commercial use. For example, bathymetric maps are important in forging different underwater communications.

Also, bathymetric maps are important tools for formulating theories about how Earth developed, along with theories of sea and ocean formation.

See also Abyssal plains; Deep sea exploration; Ocean trenches; Oceans and seas

BEACH AND SHORELINE DYNAMICS

The coast and beach, where the continents meet the sea, are dynamic environments where agents of **erosion** vie with processes of deposition to produce a set of features reflecting their complex interplay and the influences of changes in sea level, **climate**, or sediment supply. “Coast” usually refers to the larger region of a continent or island which is significantly affected by its proximity to the sea, whereas “beach” refers to a much smaller region, usually just the areas directly affected by wave action.

The earth is constantly changing. Mountains are built up by tectonic forces, weathered, and eroded away. The erosional debris is deposited in the sea. In most places these changes occur so slowly that they are barely noticeable, but at the beach we can often watch them progress.

Most features of the beach environment are temporary, steady-state features. To illustrate this, consider an excavation in **soil**, where **groundwater** is flowing in, and being pumped out by mechanical pumps. The level of the **water** in the hole is maintained because it is being pumped out just as fast as it is coming in. It is in a steady state, but changing either rate will promptly change the level of the water. A casual observer may fail to notice the pumps, and erroneously conclude that the water in the hole is stationary. Similarly, a casual observer may think that the **sand** on the beach is stationary, instead of in a steady state. The size and shape of a spit, which is a body of sand stretching out from a point, parallel to the shore, is similar to the level of the water in this example. To stay the same, the rate at which sand is being added to the spit must be exactly balanced by the rate at which it is being removed. Failure to recognize this has often led to serious degradation of the coastal environment.

Sea level is the point from which we measure elevation, and for good reason. A minor change in elevation high on a mountain is undetectable without sophisticated surveying equipment. The environment at 4,320 feet above sea level is not much different from that at 4,310 feet. The same 10-foot change in the elevation of a beach would expose formerly submerged land, or inundate formerly exposed land, making it easy to notice. Not only is the environment different, the dominant geologic processes are different: Erosion occurs above sea level, deposition occurs below sea level. As a result, coasts where the land is rising relative to sea level (emergent coasts) are usually very different from those where the land is sinking relative to sea level (submergent coasts).

If the coast rises, or sea level goes down, areas that were once covered by the sea will emerge and form part of the landscape. The erosive action of the waves will attack surfaces that previously lay safely below them. This wave attack occurs right at sea level, but its effects extend from there. Waves may undercut a cliff, and eventually the cliff will fall into the sea, removing material from higher elevations. In this way the cliff retreats, while the beach profile is extended at its base. The rate at which this process continues depends on the material of the cliff and the profile of the beach. As the process continues, the gradual slope of the bottom extends farther and farther until most waves break far from shore and the rate of cliff retreat slows, resulting in a stable profile that may persist for long periods of time. Eventually another episode of uplift is likely to occur, and the process repeats.

Emergent coasts, such as the coast along much of California, often exhibit a series of terraces, each consisting of a former beach and wave cut cliff. This provides evidence of both the total uplift of the coast, and its incremental nature.

Softer rocks erode more easily, leaving resistant **rock** that forms points of land called headlands jutting out into the sea. Subsurface depth contours mimic that of the shoreline, resulting in wave refraction when the change in depth causes the waves to change the direction of their approach. This refraction concentrates wave energy on the headlands, and spreads it out across the areas in between. The “pocket beaches” separated by jagged headlands, which characterize much of the scenic coastline of Oregon and northern California, were formed in this way. Wave refraction explains the fact that waves on both sides of a headland may approach it from nearly opposite directions, producing some spectacular displays when they break.

If sea level rises, or the elevation of the coast falls, formerly exposed **topography** will be inundated. Valleys carved out by **rivers** will become estuaries like the Chesapeake Bay. Hilly terrains will become collections of islands, such as those off the coast of Maine.

The ability of rivers to transport sediment depends on their velocities. When they flow into a deep body of water they slow down and deposit their sediment in what will eventually become a **delta**. Thus, the flooding of estuaries causes deposition further inland. As the **estuary** fills in with sediment the depth of the water will decrease, and the velocity of the water flowing across the top of the delta will increase. This permits it to transport sediment further, and the delta builds out toward, and eventually into, the sea. The additional load of all the sediment may cause the **crust** of the earth to deform, submerging the coast further.

Wave action moves incredible amounts of sand. As waves approach shallow water, however, they slow down because of friction with the bottom, get steeper, and finally break. It is during this slowing and breaking that sand gets transported. When waves reach the shore they approach it almost straight on, so that the wave front is nearly parallel to the shore as it breaks. The wave front is not exactly parallel to the shore, however, and it is this difference which moves sand along the beach.

When a breaking wave washes up onto the beach at a slight angle it moves sand on the beach with it. This movement is mostly towards shore, but also slightly down the beach. When the water sloshes back, it goes directly down the slope, without any oblique component. As a result, sand moves in a

The beach is an area of constant change, with processes of erosion and deposition constantly warring with each other. ***M. Woodbridge Williams. National Park Service.***

zigzag path with a net motion parallel to the beach. This is called "longshore drift." Although most easily observed and understood in the swash zone, the **area** of the beach which gets alternately wet and dry with each passing wave, **longshore drift** is active in any water shallow enough to slow waves down.

Many features of sandy coasts are the result of longshore drift. Spits build out from projecting land masses, sometimes becoming hooked at their end, as sand moves parallel to the shore. At Cape Cod, Massachusetts, glacial debris, deposited thousands of years ago, is still being eroded and redistributed by wave action.

An artificial jetty or "groin" can trap sand on one side of it, broadening the beach there. On the other side, however, wave action will transport sand away. Because of the jetty it will not be replenished, and erosion of the beach will result.

The magnitude and direction of transport of longshore drift depends on the strength and direction of approach of waves, and these may vary with the season. A beach with a very gentle slope, covered with fine sand every July may be a steep pebble beach in February.

Long, linear islands parallel to the shore are common along the Atlantic coast. Attractive sites for resorts and real estate developments, these **barrier islands** are in flux. A hurricane can drive storm waves over low spots, cutting islands in two. Conversely, migration of sand can extend a spit across the channel between two islands, merging them into one.

Interruptions in sand supply can result in erosion. This has happened off the coast of Maryland, where Assateague Island has gotten thinner and moved shoreward since jetties were installed at Ocean City, just to the north.

Often, the steady-state nature of the beach environment has not been properly respected. At higher elevations, where rates of erosion and deposition are so much slower, man can construct huge hills to support interstate highways, level other hills to make parking lots, etc., expecting the results of the work to persist for centuries, or at least decades. But in a beach environment, modifications are ephemeral. Maintaining a parking lot where winds would produce a dune requires removal of tons of sand-every year. Even more significantly, because the flow of sediment is so great, modifications intended to have only a local, beneficial effect may influence erosion and deposition far down the beach, in ways that are not beneficial. Tossing a drain plug into a bucket of water raises the level of the water by just a tiny amount. Putting the same drain plug into the drain of a bathtub, into which water is flowing steadily, will change the level in the tub in very substantial ways. Similarly, it may be possible to protect the beach in front of a beach house by installing a concrete barrier, but this might result in eroding the supports to the highway that provide access to the beach house.

See also Continental shelf; Drainage basins and drainage patterns; Drainage calculations and engineering; Dunes; Ocean circulation and currents; Offshore bars; Wave motions

Beaufort, Sir Francis (1774-1857)

Irish admiral

Sir Francis Beaufort, British admiral and hydrographer to the Royal Navy, was the first in 1805 to introduce and describe a scale of **wind** for estimating wind strengths without the use of instruments, a system based on subjective observations of the sea. Because expansions to land conditions were later added to the **Beaufort wind scale**, and quantitative wind speed values were also supplemented to each category in 1926, the scale is still widely used to describe the wind's speed and strength. As well as the Beaufort wind scale, the Beaufort Sea in the Arctic Ocean is named after Sir Francis Beaufort.

Sir Francis Beaufort was born in County Meath, Ireland. His father was well known in the areas of geography and **topography**: he published one of the earliest detailed maps of Ireland. Sir Francis Beaufort's nautical career began at age 13 as a cabin boy in the British Navy. Three years later, he became interested in the **weather**, and started to write down short comments about the general weather. He was only 22 years old when he was promoted to a lieutenant. In 1805, he was given his first command on the naval ship H.M.S. *Woolwich*, and he was assigned a hydrographic survey in **South America**.

During these years, Beaufort developed the first version of his wind force scale and weather notation coding, which he used for his meteorological journals. Because Beaufort's weather journal entries were written daily, eventually even as frequently as every two hours, he needed a simple yet effective system of abbreviations for the weather conditions. He created a notation consisting of the wind force number from his wind force scale, and a one, two, or three-character alphabetical code describing the state of the sky and weather, even describing cloud conditions and **precipitation** types. He continued writing these meteorological journals until the end of his life.

Beaufort's next assignments were for a hydrographic study of the Eastern Mediterranean, and a patrol mission. He did a major surveying and charting around the Turkish coast, but in 1812, he was wounded by sniper fire during a conflict with local pashas, and later that year the Admiralty ordered him home due to his injury. In 1817, he wrote his experiences about this expedition in a book titled *Karamania*. Although he remained in the British Navy until he was 81, he did not returned to active sea duty. In 1829, Beaufort became hydrographer to the Admiralty, where he promoted hydrographic studies for several British expeditions.

Between 1831 and 1836, on the voyage of the *Beagle*, Beaufort's scale of wind force was used officially for the first time. In 1833, after some slight modifications, the Admiralty prescribed Beaufort's weather notation for all log entries in the British Navy. In 1838, the Admiralty also officially adopted the Beaufort wind scale for all ships. Beaufort became a Rear Admiral in 1846, and he was bestowed the title Knight Commander of the Bath in 1848. After 68 years of service, Sir Francis Beaufort retired from the Admiralty in 1855, and he died two years later in 1857.

Originally, the Beaufort wind scale was meant for ships, specifying the amount of sail that a full-rigged ship should carry under the various wind conditions. It consisted of 13 different degrees of wind strength, ranging from calm to hurricane. In 1838, the use of the Beaufort wind scale became mandatory for all log entries on the ships of the British Admiralty. When steamboats replaced sail ships, certain modifications were necessary to make for the international use in meteorological descriptions. In 1874, the International Meteorological Committee revised the original scale, mainly for usage in international weather telegraphs. The original Beaufort scale numbers needed to be changed such that instead of the sails on a frigate, they referred to states of the sea or degrees of motion of trees. This change was still not satisfactory, since some ambiguities soon arose. The last modification came in 1946, when the International Meteorological Committee extended the scale to 17 values by adding five values to refine the hurricane-force winds, and defined the scale values by ranges of the wind speed as measured at a height of 10 meters above the surface for each category. This concluded the transformation of the Beaufort wind force scale into the Beaufort wind speed scale.

Sir Francis Beaufort was an accomplished hydrographer, making thorough surveys of uncharted coasts. Some of his charts are still used, even almost 200 years after he produced them. However, Beaufort's even more important achievements are the invention of the Beaufort wind scale, which today is still used worldwide, and the usage of the Beaufort weather notation code, which after several modifications, later became the basis for modern-day **meteorology** codes.

See also Cartography; Hydrogeology; Wave motions

BEAUFORT WIND SCALE

In 1805, to standardize nautical observations, **Sir Francis Beaufort**, an Irish hydrographer and member of the British Admiralty, created a scale for judging the strength of **wind** at sea. His scale is still a useful standard for the determination of wind force.

Each of the Beaufort Scale's 12 wind-force levels, ranging from calm to hurricane force, includes a description of the effect of the wind on readily observable, common objects. Beaufort's original purpose in devising the scale was to create a common reference for sailors to estimate and easily convey the effect of wind and sea upon their ships. Thus, the scale gives observers a means of estimating wind force.

The Beaufort Wind Scale numbers correspond to the following states (with estimated wind speeds in knots): Beaufort No.0 calm (less than 1 knot of wind); Beaufort No.1 light air (1-3 knot wind); Beaufort No.2 light breeze (4-6 knot wind); Beaufort No.3 gentle breeze (7-10 knot wind); Beaufort No.4 moderate breeze (11-16 knot wind); Beaufort No.5 fresh breeze (17-21 knot wind); Beaufort No.6 strong breeze (22-27 knot wind); Beaufort No.7 near gale (28-33 knot wind); Beaufort No.8 gale (34-40 knot wind); Beaufort No.9 strong gale (41-47 knot wind); Beaufort No.10 storm breeze (48-55 knot wind); Beaufort No.11 violent storm breeze (56-63 knot wind); Beaufort No.12 hurricane (64 or greater knot wind).

Originally limited to a description of the effects of wind on a sailing vessel's canvas (force 12, for instance, was "that which no canvas could withstand"), the scale was revised in 1939 by the International Meteorological Committee to include the effect of wind on land features. The numbers from the Beaufort scale were used on **weather** maps until 1955, when a system of wind feathers, which show wind direction and intensity, was adopted.

See also Air masses and fronts; Weather forcasting; Weather forecasting methods

BECQUEREL, ANTOINE-HENRI (1852-1908)

French physicist

Antoine-Henri Becquerel's landmark research on x rays and his discovery of radiation laid the foundation for many scientific advances of the early twentieth century. X rays were discovered in 1895 by the German physicist Wilhelm Conrad Röntgen, and in one of the most serendipitous events in science history, Becquerel discovered that the uranium he was studying gave off radiation similar to x rays. Becquerel's student, **Marie Curie**, later named this phenomenon **radioactivity**. His later research on radioactive materials found that at least some of the radiation produced by unstable materials consisted of electrons. For these discoveries Becquerel shared the 1903 Nobel Prize in physics with Marie and **Pierre Curie**. Becquerel's other notable research included the effects of **magnetism** on light and the properties of luminescence.

Becquerel was born in Paris on December 15, 1852. His grandfather, Antoine-César Becquerel, had fought at the Battle of Waterloo in 1815 and later earned a considerable reputation as a physicist. He made important contributions to the study of electrochemistry, **meteorology**, and agriculture. Antoine-Henri's father, Alexandre-Edmond Becquerel, was also scientist, and his research included studies on photography, heat, the conductivity of hot gases, and luminescence.

During his years at the Ecole des Ponts et Chaussées, Becquerel became particularly interested in English physicist Michael Faraday's research on the effects of **magnetism** on light. Faraday had discovered in 1845 that a plane-polarized beam of light (one that contains light waves that vibrate to a specific pattern) experiences a **rotation** of planes when it passes through a **magnetic field**; this phenomenon was called the Faraday effect. Becquerel developed a formula to explain the relationship between this rotation and the refraction the beam of light undergoes when it passes through a substance. He published this result in his first scientific paper in 1875, though he later discovered that his initial results were incorrect in some respects.

Although the Faraday effect had been observed in solids and liquids, Becquerel attempted to replicate the Faraday effect in gases. He found that gases (except for **oxygen**) also have the ability to rotate a beam of polarized light. Becquerel remained interested in problems of magneto-optics for years, and he returned to the field with renewed enthusiasm in 1897 after Dutch physicist Pieter Zeeman's discovery of the Zeeman effect—whereby spectral lines exposed to strong magnetic fields split—provided new impetus for research.

In 1874 Becquerel married Lucie-Zoé-Marie Jamin, daughter of J.-C. Jamin, a professor of physics at the University of Paris. She died four years later in March 1878, shortly after the birth of their only child, Jean. Jean later became a physicist himself, inheriting the chair of physics held by his father, grandfather, and great-grandfather before him. Two months prior to Lucie's death, Becquerel's grandfather died. At that point, his son and grandson each moved up one step, Alexandre-Edmond to professor of physics at the Musée d'Histoire Naturelle, and Antoine-Henri to his assistant. From that point on, Becquerel's professional life was associated with the Musée, the Polytechnique, and the Ponts et Chaussées.

In the period between receiving his engineering degree and discovering radioactivity, Becquerel pursued a variety of research interests. In following up his work on Faraday's magneto-optics, for example, he became interested in the effect of the earth's magnetic field on the atmosphere. His research determined how the earth's magnetic field affected **carbon** disulfide. He proposed to the International Congress on Electric Units that his results be used as the standard of electrical current strength. Becquerel also studied the magnetic properties of a number of materials and published detailed information on nickel, cobalt, and **ozone** in 1879.

In the early 1880s Becquerel began research on a topic his father had been working on for many years—luminescence, or the emission of light from unheated substances. In particular he made a detailed study of the spectra produced by luminescent materials and examined the way in which light is absorbed by various **crystals**. Becquerel was especially interested in the effect that polarization had on luminescence. For this work Becquerel was awarded his doctoral degree by the University of Paris in 1888, and he was once again seen as an active researcher after years of increasing administrative responsibility.

When his father died in 1891 Becquerel was appointed to succeed him as professor of physics at the museum and at the conservatory. The same year he was asked to replace the ailing Alfred Potier at the Ecole Polytechnique. Finally, in 1894, he was appointed chief engineer at the Ecole des Ponts et Chaussées. Becquerel married his second wife, Louise-Désirée Lorieux, the daughter of a mine inspector, in 1890; the couple had no children.

The period of quiescence in Becquerel's research career ended in 1895 with the announcement of Röntgen's discovery of x rays. The aspect of the discovery that caught Becquerel's attention was that x rays appeared to be associated with a luminescent spot on the side of the cathode-ray tube used in Röntgen's experiment. Given his own background and interest in luminescence, Becquerel wondered whether the production of x rays might always be associated with luminescence.

To test this hypothesis Becquerel wrapped photographic plates in thick layers of black paper and placed a known luminescent material, potassium uranyl sulfate, on top of them. When this assemblage was then placed in sunlight, Becquerel found that the photographic plates were exposed. He concluded that sunlight had caused the uranium salt to luminesce, thereby giving off x rays. The x rays then penetrated the black paper and exposed the photographic plate. He announced these results at a meeting of the Academy of Sciences on February 24, 1896.

Through an unusual set of circumstances the following week, Becquerel discovered radioactivity. As usual, he began work on February 26 by wrapping his photographic plates in black paper and taping a piece of potassium uranyl sulfate to the packet. However, because it wasn't sunny enough to conduct his experiment, Becquerel set his materials aside in a dark drawer. He repeated the procedure the next day as well, and again a lack of sunshine prompted him to store his materials in the same drawer. On March 1 Becquerel decided to develop the photographic plates he had prepared and set aside. It isn't clear why he did this—for, according to his hypothesis, little or no exposure would be expected. Lack of sunlight had meant that no luminescence could have occurred; hence, no x rays could have been emitted.

Surprisingly, Becquerel found that the plates had been exposed as completely as if they had been set in the **sun**. Some form of radiation—but clearly not x rays—had been emitted from the uranium salt and exposed the plates. A day later, according to Oliver Lodge in the *Journal of the Chemical Society*, Becquerel reported his findings to the academy, pointing out: "It thus appears that the phenomenon cannot be attributed to luminous radiation emitted by reason of phosphorescence, since, at the end of one-hundredth of a second, phosphorescence becomes so feeble as to become imperceptible."

With the discovery of this new radiation Becquerel's research gained a new focus. His advances prompted his graduate student, Marie Curie, to undertake an intensive study of radiation for her own doctoral thesis. Curie later suggested the name radioactivity for Becquerel's discovery, a phenomenon that had until that time been referred to as Becquerel's rays.

Becquerel's own research continued to produce useful results. In May 1896, for example, he found uranium metal to be many times more radioactive than the compounds of uranium he had been using, and he began to use it as a source of radioactivity. In 1900 he also found that at least part of the radiation emitted by uranium consists of electrons, particles that were discovered only three years earlier by Joseph John Thomson. For his part in the discovery of radioactivity Becquerel shared the 1903 Nobel Prize in physics with Curie and her husband Pierre.

Honors continued to come to Becquerel in the last decade of his life. On December 31, 1906, he was elected vice president of the French Academy of Sciences, and two years later he became president of the organization. On June 19, 1908, he was elected one of the two permanent secretaries of the academy, a post he held for less than two months before his death on August 25, 1908, at Le Croisic, in Brittany. Among his other honors and awards were the Rumford Medal of the Royal Society in 1900, the Helmholtz Medal of the Royal Academy of Sciences of Berlin in 1901, and the Barnard Medal of the U.S. National Academy of Sciences in 1905.

See also Geochemistry

BED OR TRACTION LOAD

Bed load, sometimes referred to as traction load, is the material that is transported by sliding, rolling, and saltating (skipping) along the bed of a stream. Particles comprising bed load can range in size from **sand** to boulders. The movement of bed load is responsible for **bedforms** that change in time and space along a stream bed.

Particles along a stream bed begin to move when the shear stress exerted by the flowing **water** exceeds a critical value. The critical shear stress depends on a combination of the particle diameter, the slope of the stream channel, the difference between the density of individual particles and that of water (particle buoyancy), and the degree to which the particles are packed together. As a result, particles of different mineralogical composition and size will have different critical shear stresses. Heavy **minerals** such as gold can be concentrated in stream beds because gold nuggets or flakes are left behind while lighter particles move around them. Likewise, small particles may move while large particles of the same mineral or **rock** type are left in place. Water density is proportional to the **suspended load** being carried. Muddy water high in suspended sediment will therefore increase the particle buoyancy and thereby reduce the critical shear stress required to move particles of a given size and composition.

The shear stress exerted by the flowing water, which is proportional to both water depth and stream channel slope, also controls the movement of bed load. Large or heavy particles that have high critical shear stress values may move as bed load when the water is unusually deep during infrequent **floods** and remain stationary between those times.

Once a particle begins to move, the current above the bed may be strong enough to lift it off the bed and into the flowing water. When the entire weight of a particle is borne by water instead of other particles beneath it, that particle ceases to be part of the bed load and becomes part of the suspended load. Conversely, if the current slows a particle may fall out of suspension and become part of the bed load. The distinction between bed load and suspended load in a stream can therefore change continuously through time.

See also Erosion; Rivers; Saltation; Sedimentation; Stream valleys, channels, and floodplains

BEDDING

The term bedding (also called stratification) ordinarily describes the layering that occurs in **sedimentary rocks** and sometimes the layering found in **metamorphic rock**. Bedding may occur when one distinctly different layer of sediment is deposited on an older layer, such as **sand** and pebbles deposited on silt or when a layer of exposed sedimentary **rock** has a new layer of sediments deposited on it. Such depositions of sediments produce a clear division between beds called the bedding plane.

The variation among different sedimentary rock layers (usually referred to as beds or strata) may range from subtle to very distinct depending upon color, composition, cementation, texture, or other factors. One of the best examples may be seen in Arizona's Grand **Canyon** where red, green, white, gray, and other colors heighten the contrast between beds.

The bedding found in metamorphic rock that formed from sedimentary rock is evidence of extreme heat and pressure and is often quite distorted. Distortions may change the sedimentary bedding by compressing, inclining, folding, or other changes.

One of the most common types of bedding is called graded bedding. These beds display a gradual grading from the bottom to the top of the bed with the coarsest sediments at the bottom and the finest at the top. Graded bedding often occurs when a swiftly moving river gradually slows, dropping its heaviest and largest sediments first and lightest last. Changes in a river's speed may be caused by a number of factors, including storm **runoff** or the entry of a river into a lake or an ocean.

Bedding is usually found in horizontal layers called parallel bedding. But bedding may be inclined or have a swirly appearance. Inclined bedding may occur when sediments are deposited on a slope, such as a sand dune, or when beds are tilted from their original horizontality by forces within the earth. Bedding with a swirly appearance, called cross bedding, may indicate that the sediments making up the rock were deposited by strong **desert** winds or turbulence in a river.

The origin, composition, and interpretation of variations in bedding are one of the geologist's most important tools in studying Earth's history. It is for this reason that **stratigraphy**, the study which includes the interpretation of sedimentary and metamorphic beds, was an essential part of even the earliest days of geologic research.

See also Superposition

BEDFORMS (RIPPLES AND DUNES)

Centimeter to meter-scale layering, or **bedding**, is a defining characteristic of **sedimentary rocks**. Non-horizontal depositional beds are called bedforms, and geologists refer to the lithified remains of bedforms in sedimentary rocks as cross bedding. Patterns of stratification, including cross bedding, allow sedimentary geologists called stratigraphers to deduce the dynamic processes that occurred in ancient sedimentary environments.

Atmospheric and aqueous currents create bedforms. When **wind** or **water** carries loose grains across a horizontal bed of unconsolidated sediment, regular geometric patterns develop on the surface of the bed. These structures vary in size from very small ripples, to medium-sized waves and megaripples, to large and very large **dunes**. The velocity, direction, constancy, and homogeneity of the current, or flow field, determines the size and shape of the resulting bedform field. For example, a one-directional flow field like a river current tends to create asymmetrical bedforms, whereas bidirectional currents like **tides** or waves deposit symmetrical ripples and dunes.

Bedforms migrate over time. Sometimes the flow field is strong enough, or the bedforms are small enough, that migration occurs by erasure of the entire bedform field, and formation of a new pattern of ripples or dunes. Ripples typically migrate by this type of wholesale reshaping. Ripples preserved in sedimentary rocks suggest that the ripples froze in their final configuration, either because the flow field waned to a point where it could no longer transport sediment, or perhaps that rapid deposition of an overlying bed buried them. Larger bedforms, including aqueous and wind-formed, or Eolian, dunes, migrate by a process in which the water or wind picks up grains from the upstream face of the bedform and deposits them on deposits them on the downstream face. This process creates a composite bedform with inclined internal beds. When dunes are lithified, this internal stratification is preserved as cross bedding.

See also Eolian processes; Sedimentation; Stratigraphy

BEDROCK

Bedrock (also termed Bed **rock**) is a layer of undisturbed rock usually located beneath a surface layer of **soil** or other material. In areas of high **erosion**, bedrock may become exposed to the surface. Bedrock can be of igneous, sedimentary, or metamorphic origin and forms the upper surface of the rocky foundation that composes the earth's **crust**.

A surface exposure of bedrock is called an outcrop. Bedrock is only rarely exposed, or crops out, where sediment accumulates rapidly, for example, in the bottom of **stream valleys** and at the base of hills or mountains. Outcrops are common where erosion is rapid, for example, along the sides of steep stream channels and on steep hill or mountain slopes. Deserts and mountain tops above the treeline also host good bedrock exposures due to the scarcity of vegetation, and resulting rapid erosion. Man-made outcrops are common where roadways cut through mountains or hilltops, in quarries, and in mines

Generally, the more rock resists erosion, the more likely it is to crop out. **Granite** and **sandstone** commonly form well-exposed outcrops. Natural exposures of shale and claystone, both soft, fine-grained rocks, are rare—especially in humid climates.

In addition to the occasional mineral crystal or **fossils**, all outcrops contain through-going fractures called joints. These form during the application of stresses to bedrock on a regional scale, for example, during mountain building. Even greater stresses may cause faulting movement of the rock on the sides of a fracture. An example is the large-scale bedrock movement that occurs along the San Andreas Fault in California. When stresses cause plastic rather than brittle deformation of bedrock, it **folds** rather than faulting.

Bedrock is distributed in a predictable pattern. Generally in the central **area** of a continent, geologists find very ancient (one billion years or more) **mountain chains**, consisting of igneous and **metamorphic rock**, eroded to an almost flat surface. This area, called a continental shield, typically contains the oldest continental bedrock. Shields have experienced multiple episodes of deformation so they are intensely folded and faulted. These ancient igneous and metamorphic rocks, called basement rocks, compose much of the continental crust. However, on the shield margins, thick sequences of relatively undeformed, **sedimentary rocks** cover the basement rocks. These deposits, called the continental platform, commonly exceed 1 mi (1.6 km) in thickness and 100 million years in age.

Together, the shield and platform make up the bedrock area known as the continental **craton**. The craton is considered more or less stable, that is, it is not currently experiencing significant deformation. On the margins of the craton, there may be areas of geologically active bedrock, called orogens, from the Greek word for mountain. Orogens are relatively young mountain belts where uplift, folding, faulting, or volcanism occurs. The bedrock here varies in age from **lava** flows that may be only days old to igneous, sedimentary, and metamorphic rock that are hundreds of millions of years old. All bedrock belongs to the continental shield, platform, or the orogens.

See also Earth, interior structure; Faults and fractures; Pluton and plutonic bodies; Soil and soil horizons; Weathering and weathering series

BEEBE, CHARLES WILLIAM (1887-1962)

American explorer

Charles William Beebe (1877–1962), explorer, writer, ornithologist, and deep-sea pioneer, was born in Brooklyn, New York and grew up in East Orange, New Jersey. He is remembered today primarily for his record-breaking 1934 descent off the coast of Bermuda with American engineer Otis Barton. Barton and Beebe dove in a diving machine of their own invention, the bathysphere, to a depth of 3,028 feet (923 m).

Beebe's parents were fascinated by natural history, and so in childhood he was a frequent visitor to the American Museum of Natural History in New York City. As a teenager, Beebe taught himself taxidermy and became friends with the president of the museum, Henry Osborn. Osborn helped him gain admittance to Columbia University in 1896. In 1899, Beebe left college (without receiving a degree) to work as an assistant curator of ornithology (the study of birds) at the zoo then being opened by the New York Zoological Society. He was soon promoted to full curator.

In 1902, Beebe married Mary Rice, whom he was to divorce in 1913. The Beebes made ornithological expeditions to Mexico, Trinidad, and Venezuela and published popular accounts of their experiences. In 1909–1911 they traveled to the Far East on a 17-month expedition sponsored by the New York Zoological Society having the sole purpose of studying pheasants. After years of further labor Beebe published the results of this expedition in a magisterial four-volume work entitled *A Monograph of the Pheasants*, (1918), still in print. While preparing his monograph Beebe also made expeditions to **Asia**, Central and **South America**, the Galapagos Islands, and other regions. In 1916 he established a research station on the coast of British Guiana (today Guyana) on behalf of the New York Zoological Society, and in 1919 was made director of the Society's Department of Tropical Research.

In the mid 1920s Beebe's main interest turned from birds to deep-sea life, which he studied by trawling for specimens and by diving in pressure suits. However, the suits were limited in depth range and the creatures brought to the surface by Beebe's nets were invariably dead. Wishing to observe undamaged specimens alive in their natural habitat, Beebe publicized his need for a practical deep-sea vessel design.

In 1928, Beebe was approached by Otis Barton with his design for the bathysphere (derived from the Greek word for deep, *báthys*), a steel ball filled with breathable air that would be lowered on a cable from a barge. The bathysphere was equipped with two **quartz** portholes 8 inches (0.2 m) wide and with an umbilical hose providing telephone and power. **Oxygen** was supplied from on-board tanks and **carbon dioxide** was removed from the air by trays of soda lime. The bathysphere was a tiny craft—only four feet, nine inches (1.5 m) across (outside diameter), with walls several inches thick. Its interior would have been a tight squeeze for a single person, but Barton and Beebe occupied it along with the oxygen tanks, soda lime trays, and other gear.

Barton and Beebe made a number of bathysphere descents starting in 1930. The pre-bathysphere dive record was 525 feet (160 m); on August 15, 1934, Barton and Beebe dove to 3,028 feet (923 m)—over half a mile. Beebe described the descent in a book published later that year, *Half Mile Down*. Barton and Beebe's bathyspheric dives were the first diving expeditions to penetrate to depths beyond the effective reach of sunlight; below 2,000 feet (610 m), they observed, the ocean was lightless even with a brilliant tropical **sun** shining on calm **seas** above. The dives were widely popularized by the *National Geographic* magazine, in Beebe's own colorful writings, and for one dive in 1932 by live radio broadcast in the United States and United Kingdom. Even before their record dive in 1934, Barton and Beebe were international celebrities.

Despite its successes, the bathysphere was inherently dangerous. Surface waves could easily subject the suspension cable to breaking strain. Later generations of deep-sea vessels have therefore been built as self-propelled submarines.

Barton and Beebe's 1934 diving record remained unbroken until 1949, when Barton descended to 4,500 feet (1,370 m) in another vessel of his own design, the Benthoscope. Beebe retired from the directorship of the New York Zoological Society's Department of Tropical Research in 1952 and died of natural causes in Bermuda in 1962.

The original bathysphere resides in the New York Aquarium in New York City.

See also Deep sea exploration; History of exploration III (Modern era); Oceanography

BENETT, ETHELDRED (1776-1845)

English geologist

Etheldred Benett, arguably the first female geologist, was born in England in 1776, the same year the American Revolutionary War began. Benett lived in Wiltshire county, southern England, and contributed to the founding of biostratigraphy.

Benett's understanding of the context of **fossils** put her in touch with many of the famous geologists of the day. She corresponded with and met many, from Professor William Buckland at Oxford and the famous Sussex paleontologist, Gideon Mantell to **Charles Lyell**, founder of the principle of **uniformitarianism,** and **William Smith**, the father of **stratigraphy** and producer of the first map of Britain in 1815.

Benett's contributions to **geology** lie in four areas. First, she commissioned the first recorded measured section at the Upper Chicksgrove Quarry, Tisbury in Wiltshire. This was donated to the Geological Society of London Library and signed by her in 1815. Second, she was a recognized expert regarding fossil mollusks and sponges of Wiltshire, as attested to by her contributions to Sowerby's publication. Third, the Czar of Russia gave her a medal for her contribution to his fossil collection because he thought she was a man. She also received a Diploma of appointment as a member of the Imperial Natural History Society of Moscow to which she makes the comment in a letter, "In this diploma I am called Dominum Etheldredum Benett and Mr Lyell told me that he had been written to by foreigners to know if Miss Benett was not a gentleman." The Latinized suffix "um" in her name implies that the sender thought she was male. Finally, she pushed forward the boundaries of biostratigraphy. Etheldred Benett published a classic volume in 1831, *Organic Remains of the County of Wiltshire* with extensive drawings, which she herself produced. She also contributed generously and extensively to Sowerby's *Mineral Conchology* (published in 1816). She gave the second highest number of specimens to this volume of any contributor.

Etheldred Benett never married, instead devoting her life to her fossil collection until she died at the age of 69. Her extensive collection of thousands of labeled Jurassic and Cretaceous fossils was thought to be so valuable a resource that when she died, most of her collection was bought by former Englishman and physician Thomas Wilson of Newark, Delaware; it then was taken to America. The collection was subsequently donated to the Philadelphia Academy of Natural Science between 1848 and 1852. The collection contains some of the first fossil bivalves to have their soft parts preserved.

Etheldred Benett was, therefore, at the forefront of paleontology and biostratigraphy at a time when many people still assumed that fossils were deposited from catastrophic acts of religious significance (such as Noah's flood), and that scientific investigation should be left solely to men.

See also Fossil record; Fossils and fossilization; Historical geology

BENIOFF ZONE

Benioff zones are dipping, roughly planar zones of increased **earthquake** activity produced by the interaction of a downgoing oceanic crustal plate with an overriding continental or oceanic plate. They occur at boundaries of crustal plates called subduction zones. The earthquakes can be produced by slip along the subduction thrust fault or by slip on faults within the downgoing plate, as a result of bending and extension as the plate is pulled into the mantle. The zones have dips typically ranging from 40 to 60 degrees. The zones are also known as the Wadati-Benioff zone.

During the past century, improvements in seismic acquisition and processing led to the observation that the world's earthquakes are not randomly distributed over the earth's surface. Rather, they tend to be concentrated in narrow zones along the boundaries of continental and oceanic crustal plates. According to the plate tectonic theory, the **crust** of the earth is broken into a mosaic of seven major rigid plates floating over a much less rigid mantle. The plates are not static but are in constant motion. Most of the tectonic activity, such as the formation of mountain belts, earthquakes, and volcanoes, occurs at the plate boundaries. There are four different types of these seismic zones corresponding to the four main types of plate boundary interactions: subduction zones as along the western coast of **South America**; strike-slip (transform) zones like the San Andreas system along the west coast of **North America**; zones of seismic activity along midocean ridges like the mid-Atlantic Ridge system; and continental-continental collision zones such as the Himalyan where the Indian subcontinent is ploughing into **Asia**.

Benioff zones are found in subduction zones that form by the collision of two crustal plates of dissimilar density and thickness, for example an oceanic and continental plate. The heavier (thinner) crust of the oceanic plate is thrust or subducted under the lighter and much thicker crust of the continental plate. A deep ocean trench is produced where these two plates meet. Along the Peru-Chile trench, the Pacific plate is being subducted under the South American plate, which responds by crumpling to form the Andes. The earthquake zones that parallel the great oceanic trenches are typically inclined from 40 to 60 degrees from the horizontal and extend several hundred kilometers into the mantle along trends that reach thousands of kilometers in length. These zones are sometimes called Wadati-Benioff zones after two of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States.

Benioff zones are the seismic expression of the deformation produced by the subduction of one plate under another. The subduction or "destruction" of the oceanic crust compensates for the creation of new ocean crust at the ocean ridges. The compensating result of both processes explains why the earth may not have significantly increased in size since its formation 4.6 billion years ago.

See also Continental drift theory; Plate tectonics; Sea-floor spreading

BENTHIC FORAMINIFERA • *see* CALCAREOUS OOZE

BERNER, ROBERT A. (1935-)

American geochemist

Robert A. Berner's research in sedimentary **geochemistry** led to the application of mathematical models to describe the physical, chemical, and biological changes that occur in ocean sediment. Berner, a professor of **geology** and geophysics at Yale University, also developed a theoretical approach to explain larger geochemical cycles, which led to the creation of a model for assessing atmospheric **carbon dioxide** levels and the **greenhouse effect** over geological time. A prolific researcher, Berner has written many scientific journal articles and is one of the most frequently quoted earth scientists in the *Science Citation Index.*

Robert Arbuckle Berner was born in Erie, Pennsylvania, on November 25, 1935, to Paul Nau Berner and Priscilla (Arbuckle) Berner. As a young man, Berner decided to become a scientist because of his propensity for logical thinking. "Science forces you to seek the truth and see both sides of an argument," he told Patricia McAdams. Berner began his academic studies at the University of Michigan where he earned his B.S. in 1957 and his M.S. a year later. He then went to Harvard University and earned his Ph.D. in geology in 1962. He married fellow geology graduate student Elizabeth Marshall Kay in 1959; the couple have three children.

Berner began his professional career at the Scripps Institute of **Oceanography** in San Diego, where he won a fellowship in oceanography after graduating from Harvard. In 1963, he was appointed assistant professor at the University of

Chicago, and two years later he became an associate professor of geology and geophysics at Yale University. Since 1968, Berner has also served as associate editor or editor of the *American Journal of Science.* He was promoted to full professor at Yale in 1971, and in 1987 he became the Alan M. Bateman Professor of geology and geophysics.

Principles of Chemical Sedimentology, which Berner published in 1971, reflects the interest that has fueled much of his research. Berner sees the application of chemical thermodynamics and kinetics as a valuable tool in unveiling the secrets of sediments and **sedimentary rocks**. Thus, Berner's is an unconventional approach to sedimentology (the chemical study of sediments rather than the study of chemical sediments). Berner identifies his goal in *Principles of Chemical Sedimentology* as illustrating "how the basic principles of physical **chemistry** can be applied to the solution of sedimentological problems." Berner's *Early Diagenesis,* published in 1980, is a study of the processes over geological time whereby sedimentary materials are converted into **rock** through chemical reactions or compaction. Because of the frequency with which *Early Diagenesis* has been quoted, it was declared a Science Citation Classic by the Institute for Scientific Information.

Berner observes in *Scientific American* that ''the familiar biological **carbon** cycle—in which atmospheric carbon is taken up by plants, transformed through photosynthesis into organic material and then recovered form this material by respiration and bacterial decomposition—is only one component of a much larger cycle: the geochemical carbon cycle." Berner has studied an aspect of this geochemical carbon cycle that is analogous to the transfer of carbon between plants, animals, and their habitats—the "transfer of carbon between sedimentary rocks at or near the earth's surface and the atmosphere, **biosphere** and oceans." Carbon dioxide is vital to both these aspects of the geochemical carbon cycle, as carbon is primarily stored as carbon dioxide in the atmosphere. Berner's research has contributed to the "BLAG" model (named after Berner and his associates Antonio L. Lasaga and Robert M. Garrels) for assessing the changes in atmospheric levels of carbon dioxide throughout the earth's geological eras. First published in 1983 and subsequently refined, the BLAG model quantifies factors such as degassing (whereby carbon dioxide is released from beneath the earth), carbonate and silicate rock **weathering**, carbonate formation in **oceans**, and the rate at which organic matter is deposited on and buried in the earth that enable scientists to assess the climactic conditions of the planet's previous geological eras.

Berner's research on atmospheric carbon dioxide levels includes the study of the greenhouse effect, whereby carbon dioxide and other gases trap excessive levels of radiated heat within Earth's atmosphere, leading to a gradual increase in global temperatures. Since the nineteenth-century industrial revolution, this phenomenon has increased primarily because of the burning of fossil **fuels** such as **coal**, oil, and **natural gas**; also because of deforestation. Berner reports in *Scientific American* that "slow natural fluctuations of atmospheric carbon dioxide over time scales of millions of years may rival or even exceed the much faster changes that are predicted to arise from human activities." Thus, the study of the carbon cycle is essential to an objective evaluation of the greenhouse effect within larger geological processes. In 1986, Berner published the textbook *The Global Water Cycle: Geochemistry and Environment* which he co-authored with his wife Elizabeth, who is also a geochemist. *The Global Water Cycle* reviews the properties of **water**, marine environments, and water/energy cycles, and includes a discussion of the greenhouse effect. Berner's research has since focused on Iceland where he is investigating how volcanic rock is broken down by weathering and by the plant-life that gradually takes root on it.

Berner enjoys traveling that is associated with his research and likes to help students learn to think creatively for themselves. "I'm very proud of the...graduate students that have received Ph.D.s working with me. I've learned as much from them as they have from me," he told McAdams. Berner served as president of the Geochemical Society in 1983, and he is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, the Geological Society of America, and the Mineral Society. He has chaired the Geochemical Cycles Panel for the National Research Council and served on the National Committee on Geochemistry, the National Science Foundation Advisory Committees on Earth Sciences and Ocean Sciences, and the National Research Council Committee on Oceanic Carbon. He has received numerous awards, including an honorary doctorate from the Université Aix-Marseille III in France in 1991 and Canada's Huntsman Medal in Oceanography in 1993. His hobbies include Latin American music, tennis, and swimming.

See also Greenhouse gases and greenhouse effect; Weathering and weathering series

BERNOULLI, DANIEL (1700-1782)

Dutch-born Swiss physicist

Daniel Bernoulli's work on fluids pioneered the sciences of hydrodynamics and **aerodynamics**. Born in the Netherlands and spending most of his life in Switzerland, Bernoulli was one of a large family of scientists and mathematicians that included his father, Jean Bernoulli, and uncle, Jacques Bernoulli.

Ignoring his family's pleas to enter the world of business, Bernoulli pursued a degree in medicine and then, after graduation, a career as a professor of mathematics. He began teaching in 1725 at a college in St. Petersburg, Russia, eventually returning to Switzerland in 1732. While a professor at the University of Basel, he became the first scientist outside of Great Britain to fully accept Newtonian **physics**. It was also here that Bernoulli performed the research on fluid behavior that would make him famous.

The 1738 publication *Hydrodynamica* developed the prominent theories of hydrodynamics, or the movement of **water**. Paramount among these was the fact that, as the velocity of a fluid increases, the pressure surrounding it will decrease. Called **Bernoulli's principle**, this pressure drop was also shown to occur in moving air, and it is the reason boats and planes experience lift as water or air passes around them. This effect is easily shown by blowing between two pieces of paper; the drop in pressure will cause the papers to bend toward each other. Bernoulli's research marked the first attempt to explain the connection pressure and **temperature** have with the behavior of gas and fluids.

Bernoulli's experiments with fluids caused him to devise a series of hypotheses about the nature of gases. He was certainly one of the first to formulate principles dealing with gases as groups of particles, which later became the basis for atomic theories. As groundbreaking as this work was, it was paid little attention by his peers, and subsequently it was nearly a century before the **atomic theory** rose again.

See also Atmospheric pressure; Atomic theory; Hydrostatic pressure

BERNOULLI'S PRINCIPLE

Bernoulli's principle describes the relationship between the pressure and the velocity of a moving fluid (i.e., air or **water**). Bernoulli's principle states that as the velocity of fluid flow increases, the pressure exerted by that fluid decreases.

During the late eighteenth century, **Daniel Bernoulli** pioneered the basic tenet of kinetic theory, that molecules are in motion. He also knew that flowing fluids exerted less pressure, but he did not connect these ideas logically. In *Hydrodynamica*, Bernoulli's logic that flow reduced pressure was obscure, and his formula was awkward. Bernoulli's father Johann, amid controversy, improved his son's insight and presentation in *Hydraulica*. This research was centered in St. Petersburg where Leonard Euler, a colleague of Bernoulli and a student of Johann, generalized a rate-of-change dependence of pressure and density on speed of flow. Bernoulli's principle for liquids was then formulated in modern form for the first time.

In this same group of scientists was D'Alembert, who found paradoxically that fluids stopped ahead of obstacles, so frictionless flow did not push.

Progress then seems to have halted for about a century and a half until Ludwig Prandtl or one of his students solved Euler's equation for smooth streams of air in order to have a mathematical model of flowing air for designing wings. Here, speed lowers pressure more than it lowers density because expanding air cools, and the ratio of density times degrees-kelvin divided by pressure is constant for an ideal-gas.

More turbulent flow, as in atmospheric winds, requires an alternative solution of Euler's equation because mixing keeps air-temperature fixed.

Bernoulli's principle is regarded by many as a paradox because currents and winds upset things, but standing a stick in a stream of water helps to clarify the enigma. One can observe calm, smooth, level water ahead of the stick and a cavity of reduced pressure behind it. Calm water pushes the stick, as lower pressure downstream fails to balance the upsetting force.

Bernoulli's principle never acts alone; it also comes with molecular entrainment. Molecules in the lower pressure of faster flow aspirate and whisk away molecules from the higher pressure of slower flow. Solid obstacles such as airfoils carry a thin stagnant layer of air with them. A swift low-pressure airstream takes some molecules from this boundary layer and reduces molecular impacts on that surface of the wing across which the airstream moves faster.

See also Atmospheric chemistry; Hydrostatic pressure

BESSEL, FRIEDRICH (1784-1846)

German astronomer

Friedrich Bessel was a self-taught astronomer. Born in Minden, Germany in 1784, he became an accountant in Bremen, but his true interests were **astronomy** and mathematics. In fact, in 1806, at the age of 20, he recalculated the orbit of Halley's comet, which was due to reappear in 1835. This so impressed astronomer Heinrich Olbers (1758–1840) that Olbers helped Bessel obtain a post at the observatory.

Bessel worked laboriously. He produced a new star catalogue of over 50,000 stars and introduced improvements to astronomical calculations, developing a method of mathematical analysis along the way that can be applied to many problems not related to astronomy. He oversaw construction of the first large German observatory and served as its director from 1813 until his death in 1846.

Bessel's greatest achievement was in determining the parallax of a star. As the earth orbits the **sun**, our position relative to any star shifts by a maximum of 186 million miles (299,274,000 km, the diameter of the earth's orbit). Thus, the apparent position of any star in the sky will change slightly through the year. The amount of observed shift is the parallax. Knowing an object's parallax, it is possible to calculate the distance to it.

In 1838, Bessel announced he had obtained the parallax for a star called 61 Cygni. He had chosen this star because it had shown the largest proper motion of any known star. The large degree of movement, he assumed, was because the star was relatively close, and the closer an object, the greater its parallax would be.

Bessel's calculations showed that 61 Cygni was about 10 light-years from Earth. (This was the introduction of the term light-year.) Although that is actually very close for a star, the distance was mind boggling in 1838. The earlier astronomer **Johannes Kepler** had believed the stars were 0.1 light-year away, and Isaac Newton had risked enlarging that to two light-years.

Discovering the parallax of a star also put another nail in the coffin of the "Earth-centered" concept of the universe. Since parallax could be obtained from a *moving* Earth, Nicholas Copernicus's assertion that the Earth orbited around the sun was further strengthened.

In 1841, Bessel drew a remarkable conclusion about the stars Sirius and Procyon. He had noticed displacements in their motion that could not be attributed to parallax. A parallax shift shows smooth motion; these two stars seemed to be wobbling. He concluded that there had to be invisible companions in orbit around each star. The gravitational tug of the companion would account for the observed wobble. This theory later turned out to be correct.

Bessel was responsible for encouraging astronomers to direct their attention to the stars beyond the **solar system**.

BIG BANG THEORY

Big bang theory describes the origin of the knowable universe and the development of the laws of **physics** and **chemistry** some 15 billion years ago.

During the 1940s Russian-born American cosmologist and nuclear physicist George Gamow (1904–1968) developed the modern version of the big bang model based upon earlier concepts advanced by Russian physicist Alexander (Aleksandr Aleksandrovich) Friedmann (also spelled as Fridman, 1888–1925) and Belgian astrophysicist and cosmologist Abbé Georges Lemaître (1894–1966). Big bang based models replaced static models of the universe that described a homogeneous universe that was the same in all directions (when averaged over a large span of **space**) and at all times. Big bang and static cosmological models competed with each other for scientific and philosophical favor. Although many astrophysicists rejected the steady state model because it would violate the law of mass-energy conservation, the model had many eloquent and capable defenders. Moreover, the steady state model was interpreted by many to be more compatible with many philosophical, social, and religious concepts centered on the concept of an unchanging universe. The discovery of **quasars** and a permeating cosmic background radiation eventually tilted the cosmological argument in favor of big bang theory models.

Before the twentieth century, astronomers could only assume that the universe had existed forever without change, or that it was created in its present condition by divine action at some arbitrary time. Evidence that the universe was evolving did not begin to accumulate until the 1920s. The theory that all matter in the universe was created from a gigantic explosion called the "big bang" is widely accepted by students of **cosmology**.

It was German-American physicist Albert Einstein's (1879–1955) theory of relativity, published in 1915, that set the stage for the conceptual development of an expanding universe. Einstein had designed his theory to fit a static universe of constant dimensions. In 1919, a Dutch astronomer, Willem de Sitter, showed Einstein's theory could also describe an expanding universe. Mathematically, de Sitter's solution for Einstein's equation was sound, but observational evidence of expansion was lacking, and Einstein was skeptical.

In 1929, American astronomer Edwin Powell Hubble made what has been called the most significant astronomical discovery of the century. He observed large red shifts in the spectra of the galaxies he was studying; these red-shifts indicated that the galaxies are continually moving apart at tremendous velocities. Vesto Melvin Slipher, who took photographs of the red-shift of many of the same galaxies, also drew similar conclusions.

Like de Sitter, Lemaître, who worked with Hubble in 1924, developed out a simple solution to Einstein's equations that described a universe in expansion. Hubble's stunning observation provided the evidence Lemaître was seeking for his theory. In 1933, Lemaître clearly described the expansion of the universe. Projecting *back* in time, he suggested that the universe had originated as a great "cosmic egg," expanding outward from a central point. He did not, however, consider whether an explosion actually took place to initiate this expansion. George Gamow further investigated the origin of the universe in 1948. Because the universe is expanding outward, he reasoned, it should be possible to calculate backward in time to its beginning. If all the mass of the universe was compressed into a small volume 10–15 billion years ago, its density and **temperature** must have been phenomenal. A tremendous explosion would have caused the start of the expansion, left a "halo" of background radiation, and formed the atomic elements that are heavier than the abundant hydrogen and helium. Physicists Ralph A. Alpher and Robert C. Herman established a model to show how such heavier particles could form under these conditions.

Gamow's theory implied there was a specific beginning and end to the universe. However, a number of other scientists, including Fred Hoyle, Thomas Gold, and Hermann Bondi felt that the theory of expansion required no beginning or end. Their model, called the steady state theory, suggested that matter was being continuously created throughout the universe. As galaxies drifted apart, matter would "condense" to form new ones in the void left behind. For nearly two decades, supporters of the competing theories seemed to be on equal footing.

In 1965 Robert H. Dicke made calculations relative to the cooling-off period after the initial big bang explosion. His results indicated that Gamow's residual radiation should be detectable. During the intervening eons it would have cooled to about 5 K (five kelvins above absolute zero). Unknown to him, radio engineers **Arno Penzias** and **Robert W. Wilson** already detected such radiation at 3 K in 1964 while looking for sources of **satellite** communication interference. This was the most convincing evidence yet gathered in support of the big bang theory, and it sent the steady-state theory into decline.

No theory exists today that can account for the extreme conditions that existed at the moment of the big bang. The theory of relativity does not apply to objects as dense and small as the universe must have been prior to the big bang. Cosmologists can project only as far back as 0.01 seconds after the explosion, when the cosmos was a seething mass of protons and neutrons. (It is possible there were many exotic particles that later became important as dark matter.) Based on their theories, cosmologists suggest that during this time neutrinos were produced.

It is argued that the laws of physics and chemistry—manifested in the properties of the fundamental forces of **gravity**, the strong force, electromagnetism, and the weak force (electromagnetism and the weak force are now known to be different manifestations of a more fundamental electroweak force)—formed in the first few fractions of a second of the big bang. Protons and neutrons began to form atomic nuclei about three minutes and 46 seconds after the explosion, when the temperature was a mere 900,000,000 K. After 700,000 years hydrogen and helium formed. About one billion years after the big bang, stars and galaxies began to appear from the expanding mass. Countless stars would condense from swirling nebulae, evolve and die, before our **Sun** and its planets could form in the Milky Way galaxy.

Although the big bang theory accounts for most of the important characteristics of the universe, it still has weaknesses. One of the biggest of these involves the "homogeneity" of the universe. Until 1992, measurements of the background radiation produced by the big bang have shown that matter in the early universe was very evenly distributed. This seems to indicate that the universe evolved at a constant rate following the big bang. But if this is the case, the clumps of matter that we see (such as stars, galaxies, and clusters of galaxies) should not exist.

To remedy this inconsistency, Alan Guth proposed the inflationary theory, which suggests that the expansion of the universe initially occurred much faster. This concept of accelerated expansion allows for the formation of the structures we see in the universe today.

In April 1992, NASA made an electrifying announcement: its Cosmic Background Explorer (COBE), looking 15 billion light-years into space (hence, 15 billion years into the past), detected minute temperature fluctuations in the cosmic background radiation. It is believed these ripples are evidence of gravitational disturbances in the early universe that could have resulted in matter to clumping together to form larger entities. This finding lends support to Guth's theory of inflation.

See also Astronomy; Atom; Atomic theory; Catastrophism; Cosmic microwave background radiation; Cosmology; Earth (planet)

BIOGEOCHEMICAL CYCLES

The term biogeochemical cycle refers to any set of changes that occur as a particular element passes back and forth between the living and non-living worlds. For example, **carbon** occurs sometimes in the form of an atmospheric gas (**carbon dioxide**), sometimes in rocks and **minerals** (**limestone** and **marble**), and sometimes as the key element of which all living organisms are made. Over time, chemical changes occur that convert one form of carbon to another form. At various points in the carbon cycle, the element occurs in living organisms and at other points it occurs in the earth's atmosphere, **lithosphere**, or hydrosphere.

The universe contains about ninety different naturally occurring elements. Six elements—carbon, hydrogen, **oxygen**, nitrogen, sulfur, and phosphorus—make up over 95% of the mass of all living organisms on Earth. Because the total amount of each element is essentially constant, some cycling process must take place. When an organism dies, for example, the elements of which it is composed continue to move through a cycle, returning to the earth, to the air, to the ocean, or to another organism.

All biogeochemical cycles are complex. A variety of pathways are available by which an element can move among hydrosphere, lithosphere, atmosphere, and **biosphere**. For instance, nitrogen can move from the lithosphere to the atmosphere by the direct decomposition of dead organisms or by the reduction of nitrates and nitrites in the **soil**. Most changes in the nitrogen cycle occur as the result of bacterial action on one compound or another. Other cycles do not require the intervention of bacteria. In the sulfur cycle, for example, sulfur dioxide in the atmosphere can react directly with compounds in the earth to make new sulfur compounds that become part of the lithosphere. Those compounds can then be transferred directly to the biosphere by plants growing in the earth.

Most cycles involve the transport of an element through all four parts of the planet—hydrosphere, atmosphere, lithosphere, and biosphere. The phosphorous cycle is an exception since phosphorus is essentially absent from the atmosphere. It does move from biosphere to the lithosphere (when organisms die and decay) to the hydrosphere (when phosphorous-containing compounds dissolve in **water**) and back to the biosphere (when plants incorporate phosphorus from water).

Hydrogen and oxygen tend to move together through the planet in the **hydrologic cycle**. **Precipitation** carries water from the atmosphere to the hydrosphere and lithosphere. It then becomes part of living organisms (the biosphere) before being returned to the atmosphere through respiration, transpiration, and **evaporation**.

All biogeochemical cycles are affected by human activities. As fossil **fuels** are burned, for example, the transfer of carbon from a very old reserve (decayed plants and animals buried in the earth) to a new one (the atmosphere, as carbon dioxide) is accelerated. The long-term impact of this form of human activity on the global environment, as well as that of other forms, is not yet known. Some scientists assert, however, that those affects can be profound, resulting in significant **climate** changes far into the future.

See also Atmospheric composition and structure; Chemical elements; Dating methods; Evolution, evidence of; Evolutionary mechanisms; Fossil record; Fossils and fossilization; Geochemistry; Geologic time; Global warming; Greenhouse gases and greenhouse effect; Hydrologic cycle; Origin of life; Petroleum; Stellar life cycle

BIOLOGICAL PURIFICATION • *See* WATER POLLUTION AND BIOLOGICAL PURIFICATION

BIOSPHERE

The biosphere is the **space** on and near Earth's surface that contains and supports living organisms and ecosystems. It is typically subdivided into the **lithosphere**, atmosphere, and hydrosphere. The lithosphere is the earth's surrounding layer composed of solid **soil** and **rock**, the atmosphere is the surrounding gaseous envelope, and the hydrosphere refers to liquid environments such as **lakes** and **oceans**, occurring between the lithosphere and atmosphere. The biosphere's creation and continuous **evolution** result from physical, chemical, and biological processes. To study these processes a multi-disciplinary effort has been employed by scientists from such fields as **chemistry**, biology, **geology**, and ecology.

The Austrian geologist Eduard Suess (1831–1914) first used the term biosphere in 1875 to describe the space on Earth that contains life. The concept introduced by Suess had little impact on the scientific community until it was resurrected by the Russian scientist Vladimir Vernadsky (1863–1945) in 1926 in his book, *La biosphere*. In that work, Vernadsky extensively developed the modern concepts that recognize the interplay between geology, chemistry, and biology in biospheric processes.

For organisms to live, appropriate environmental conditions must exist in terms of **temperature**, moisture, energy supply, and nutrient availability.

Energy is needed to drive the functions that organisms perform, such as growth, movement, waste removal, and reproduction. Ultimately, this energy is supplied from a source outside the biosphere, in the form of visible radiation received from the **Sun**. This electromagnetic radiation is captured and stored by plants through the process of photosynthesis. Photosynthesis involves a light-induced, enzymatic reaction between **carbon dioxide** and **water**, which produces **oxygen** and glucose, an organic compound. The glucose is used, through an immense diversity of biochemical reactions, to manufacture the huge range of other organic compounds found in organisms. Potential energy is stored in the **chemical bonds** of organic molecules and can be released through the process of respiration; this involves enzymatic reactions between organic molecules and oxygen to form **carbon** dioxide, water, and energy. The growth of organisms is achieved by the accumulation of organic matter, also known as biomass. Plants and some microorganisms are the only organisms that can form organic molecules by photosynthesis. Heterotrophic organisms, including humans, ultimately rely on photosynthetic organisms to supply their energy needs.

The major elements that comprise the chemical building blocks of organisms are carbon, oxygen, nitrogen, phosphorus, sulfur, calcium, and magnesium. Organisms can only acquire these elements if they occur in chemical forms that can be assimilated from the environment; these are termed available nutrients. Nutrients contained in dead organisms and biological wastes are transformed by decomposition into compounds that organisms can reutilize. In addition, organisms can utilize some mineral sources of nutrients. All of the uptake, excretion, and transformation reactions are aspects of nutrient cycling.

The various chemical forms in which carbon occurs can be used to illustrate nutrient cycling. Carbon occurs as the gaseous molecule carbon dioxide, and in the immense diversity of organic compounds that make up living organisms and dead biomass. Gaseous carbon dioxide is transformed to solid organic compounds (simple sugars) by the process of photosynthesis, as mentioned previously. As organisms grow they deplete the atmosphere of carbon dioxide. If this were to continue without carbon dioxide being replenished at the same rate as the consumption, the atmosphere would eventually be depleted of this crucial nutrient. However, carbon dioxide is returned to the atmosphere at about the same rate that it is consumed, as organisms respire their organic molecules, and microorganisms decompose dead biomass, or when wildfire occurs.

During the long history of life on Earth (about 3.8 billion years), organisms have drastically altered the chemical composition of the biosphere. At the same time, the biosphere's chemical composition has influenced which life forms could inhabit its environments. Rates of nutrient transformation have not always been in balance, resulting in changes in the chemical composition of the biosphere. For example, when life first evolved, the atmospheric concentration of carbon dioxide was much greater than today, and there was almost no free oxygen. After the evolution of photosynthesis there was a large decrease in atmospheric carbon dioxide and an increase in oxygen. Much of carbon once present in the atmosphere as carbon dioxide now occurs in fossil fuel deposits and **limestone** rock.

The increase in atmospheric oxygen concentration had an enormous influence on the evolution of life. It was not until oxygen reached similar concentrations to what occurs today (about 21% by volume) that multicellular organisms were able to evolve. Such organisms require high oxygen concentrations to accommodate their high rate of respiration.

Most research investigating the biosphere is aimed at determining the effects that human activities are having on its environments and ecosystems. Pollution, fertilizer application, changes in land use, fuel consumption, and other human activities affect nutrient cycles and damage functional components of the biosphere, such as the ozone layer that protects organisms from intense exposure to solar ultraviolet radiation, and the **greenhouse effect** that moderates the surface temperature of the planet.

For example, fertilizer application increases the amounts of nitrogen, phosphorus, and other nutrients that organisms can use for growth. An excess nutrient availability can damage lakes through algal blooms and fish kills. Fuel consumption and land clearing increases the concentration of carbon dioxide in the atmosphere, and may cause **global warming** by intensifying the planet's greenhouse effect.

Recent interest in long-term, manned space operations has spawned research into the development of artificial biospheres. Extended missions in space require that nutrients be cycled in a volume no larger than a building. The Biosphere-2 project, which received a great deal of popular attention in the early 1990s, has provided insight into the difficulty of managing such small, artificial biospheres. Human civilization is also finding that it is challenging to sustainably manage the much larger biosphere of planet Earth.

See also Atmospheric pollution; Earth (planet); Environmental pollution; Evolution, evidence of; Evolution, mechanisms of; Foliation and exfoliation; Forests and deforestation; Fossil record; Fossils and fossilization; Freshwater; Gaia hypothesis; Solar energy

BLACKETT, PATRICK MAYNARD STUART (1897-1974)

English physicist

Patrick Maynard Stuart Blackett was a physicist with wide-ranging scientific and personal interests. He is best known for his improvements to the Wilson cloud chamber leading to important discoveries about fundamental particles and cosmic rays. His contributions to the study of **magnetism** helped confirm **continental drift theory**. Throughout his career he was admired as an ingenious experimenter. Blackett was involved in British military defense strategies during World War II, but remained an outspoken critic of Western nuclear policies to the end of his life. For his work with the Wilson cloud chamber, Blackett was awarded the 1948 Nobel Prize in physics.

Blackett was born in London, England to Arthur Stuart and Caroline Frances Maynard Blackett. His grandfather had been Anglican vicar of Croydon, Surrey, and his father was a stockbroker. As a child he developed a strong interest in nature, especially birds. Intending a naval career, Blackett attended Osborne Royal Naval College and Dartmouth Royal College. He began active naval duty when World War I broke out in 1914.

After the war, while still in the navy, he studied for six months at Magdalene College, Cambridge. This experience, coupled with his sense that the navy was unlikely to pursue technological innovations, convinced him to pursue a scientific career. He left the service, graduating from Cambridge with a B.A. in physics in 1921. In 1924, Blackett married Costanza Bayon, with whom he had a daughter and a son.

Cambridge's Cavendish Laboratory under Ernest Rutherford's direction was one of the world's foremost centers of theoretical physics after World War I. When Blackett received a fellowship to continue studying there, Rutherford put him to work with the Wilson cloud chamber. A cloud chamber is a device that makes it possible to track the movements of fundamental particles. It consists of a transparent cylinder filled with supersaturated **water** vapor. The cylinder is set between the poles of an electromagnet. When charged particles are fired into it, the water vapor condenses on the resulting ions and creates trails which can be photographed.

Blackett made improvements to a cloud chamber he inherited from a previous student, and by 1924, was able to confirm Rutherford's prediction that one element could be transmuted into another artificially. By filling the cloud chamber with nitrogen gas and water vapor and bombarding the mixture with alpha particles (helium atoms), Blackett produced a hydrogen **atom** and an **oxygen** isotope.

In 1932, Blackett began a productive collaboration studying cosmic rays with the Italian physicist Giuseppe P. S. Occhialini. Cosmic rays were known to reach earth from extraterrestrial sources, but their exact composition was unclear. At the time, very few fundamental particles were postulated, and cosmic rays were thought to be high-energy photons, or light quanta.

Blackett and Occhialini further modified the cloud chamber by combining it with two Geiger counters so that they could obtain more continuous photographs of the particle tracks. After three years and many thousands of photographs, they were able to confirm the existence of the first antimatter particle, the positron, which had been predicted by Carl Anderson. The American physicist Robert A. Millikan had thought this positively charged particle was a proton, but Blackett and Occhialini showed that the particle had the same mass as an electron, and that positrons occurred in "showers" paired with equal numbers of electrons. Blackett also noted a curious high energy component of cosmic rays later found to be the meson.

In 1937, Blackett replaced W. L. Bragg at the University of Manchester and began to build a strong research facility there. With the onset of World War II, he was tapped by the British government to assist in defense measures. He served on the Tizard Committee from 1935 to 1936, and became Director of Naval Operational Research, where he made statistical analyses of the predicted results of differing military strategies.

Blackett, however, opposed Britain's efforts to develop its own nuclear weapons, and though he supported the American bomb project, he was highly critical of Allied nuclear policy during and after the war. He decried the bombing of German civilians and the use of atomic bombs at Hiroshima and Nagasaki. In 1948, his book *Military and Political Consequences of Atomic Energy* appeared (published in America as *Fear, War and the Bomb*). That same year he was also awarded the Nobel Prize, but public hostility to his political views in the climate of the early Cold War overshadowed the acclaim accompanying the prize. Blackett did not return to public service until the election of a Labor government in 1964.

In the late 1940s, Blackett became interested in **magnetism** and the **rotation** of massive bodies. The idea that all rotating bodies generate magnetism had been discussed for many years, and if confirmed would have been a major new physical theory. Based on his study of existing observations of the magnetism of the **Sun**, the earth, and some stars, Blackett thought the hypothesis was plausible. In order to test it, he devised a magnetometer that was ten thousand times more sensitive than any previous such instrument. Ultimately Blackett decided the theory was incorrect, but his interest in geological magnetism continued. He investigated the history of changes in the earth's **magnetic field** and came to support the theory of continental drift, which postulates that the earth's continents are made of crustal plates that slowly move atop a layer of molten **rock** (**magma**). His magnetometer proved to be very useful in the study of the magnetic fields of small rocks, which eventually helped to confirm continental drift.

In 1965, Blackett became president of the Royal Society, which under his leadership became international in focus. Though he was happy to be welcomed back into the public mainstream, Blackett continued making his political views known, describing himself as a Fabian Socialist and advocating a closer solidarity between scientists and the working class. He also devoted several years to studying scientific, political, and economic conditions in India. Blackett's last academic post was at London's Imperial College of Science and Technology from 1953 to 1965. During his career he received numerous awards in addition to the Nobel Prize, including twenty honorary degrees. In 1969, he was made a life peer, Baron Blackett of Chelsea. Blackett died in London at the age of 76.

See also Continental shelf; Quantum theory and mechanics

BLIZZARDS AND LAKE EFFECT SNOWS

A blizzard is a severe storm, potentially life threatening, caused by wind-driven snow. Although many blizzards involve heavy snow falls, smaller snow amounts may still be driven to blizzard conditions of low visibility and extreme **wind chill**.

The United States National **Weather** Service (NWS) takes a broader approach to the designation of a blizzard. NWS classifies a storm a blizzard if it manifests large amounts of snowfall, or has blowing snow in near gale force winds (generally about 35 mph, or 30 knots) or a combination of **wind** and snow that reduces visibility for more than a few hours. Severe conditions that are not quite blizzard-like are classified as sever winter storms.

Many areas near the **Great Lakes** in the United States and Canada are subject to frequent and severe blizzards due to lake effect snow. Lake effect snow is a meteorological phenomena created by the collision of Artic cold fronts sweeping generally west to east through Canada and the northern portion of the United States, with the relatively warmer air overlying the Great **Lakes**. Although lake effect snow can occur over any large body of **water** in the world, in **North America** lake effect snows are most frequently associated with the Great Lakes.

The combination of moist, unstable air and artic cold can produce locally heavy snows—especially on areas immediately east of the advancing cold front. Lake effect snowstorms are unique because they can manifest from otherwise dry cold fronts that produce clear cold weather in other parts of the country. Lake effect snow storms are not associated with advancing cells of low pressure, but rather dense high pressure Artic cold fronts.

Lake effect snow may contribute to more than half the annual snowfall for some areas on the east or southeast side of the Great Lakes. If winds are light enough to move the falling snow onshore, but not strong enough to blow the developing system over an **area** too quickly, snowfalls measuring 4–6 feet are possible.

Generally, the greater the **temperature** differential between the relatively warmer air over the lake and the advancing cold front, the more pronounced the lake effect snowfall. If the differential is great enough, and the moisture of the rising unstable air high enough, thundersnow may develop (a thunderstorm with snow instead of rain).

See also Land and sea breezes; Precipitation; Seasons; Weather forecasting methods; Weather forecasting

BLOUNT DUNES • *see* DUNES

BLOWING DUST • *see* DUNE FIELDS

BLUESCHIST • *see* SCHIST

BOHR MODEL

The Bohr model of atomic structure was developed by Danish physicist and Nobel laureate **Niels Bohr** (1885–1962). Published in 1913, Bohr's model improved the classical atomic models of physicists J. J. Thomson and Ernest Rutherford by incorporating **quantum theory**. While working on his doctoral dissertation at Copenhagen University, Bohr studied physicist Max Planck's quantum theory of radiation. After graduation, Bohr worked in England with Thomson and subsequently with Rutherford. During this time Bohr developed his model of atomic structure.

Before Bohr, the classical model of the **atom** was similar to the Copernican model of the **solar system** where, just as planets orbit the **Sun**, electrically negative electrons moved in orbits about a relatively massive, positively charged nucleus. The classical model of the atom allowed electrons to orbit at any distance from the nucleus. This predicted that when, for example, a hydrogen atom was heated, it should produce a continuous spectrum of colors as it cooled because its electron, moved away from the nucleus by the heat energy, would gradually give up that energy as it spiraled back closer to the nucleus. Spectroscopic experiments, however, showed that hydrogen atoms produced only certain colors when heated. In addition, physicist James Clark Maxwell's influential studies on electromagnetic radiation (light) predicted that an electron orbiting around the nucleus according to Newton's laws would continuously lose energy and eventually fall into the nucleus. To account for the observed properties of hydrogen, Bohr proposed that electrons existed only in certain orbits and that, instead of traveling between orbits, electrons made instantaneous quantum leaps or jumps between allowed orbits.

In the Bohr model, the most stable, lowest energy level is found in the innermost orbit. This first orbital forms a shell around the nucleus and is assigned a principal quantum number (n) of n = 1. Additional orbital shells are assigned values n = 2, n = 3, n = 4, etc. The orbital shells are not spaced at equal distances from the nucleus, and the radius of each shell increases rapidly as the square of n. Increasing numbers of electrons can fit into these orbital shells according to the formula $2n^2$. The first shell can hold up to two electrons, the second shell (n = 2) up to eight electrons, and the third shell (n = 3) up to 18 electrons. Subshells or suborbitals (designated s, p, d, and f) with differing shapes and orientations allow each element a unique electron configuration.

As electrons move farther away from the nucleus, they gain potential energy and become less stable. Atoms with electrons in their lowest energy orbits are in a "ground" state, and those with electrons jumped to higher energy orbits are in an "excited" state. Atoms may acquire energy that excites electrons by random thermal collisions, collisions with subatomic particles, or by absorbing a photon. Of all the photons (quantum packets of light energy) that an atom can absorb, only those that have energy equal to the energy difference between allowed electron orbits are absorbed. Atoms give up excess internal energy by giving off photons as electrons return to lower energy (inner) orbits.

The electron quantum leaps between orbits proposed by the Bohr model accounted for Plank's observations that atoms emit or absorb electromagnetic radiation only in certain units called quanta. Bohr's model also explained many important properties of the photoelectric effect described by **Albert Einstein**.

According to the Bohr model, when an electron is excited by energy it jumps from its ground state to an excited state (i.e., a higher energy orbital). The excited atom can then emit energy only in certain (quantized) amounts as its electrons jump back to lower energy orbits located closer to the nucleus. This excess energy is emitted in quanta of electromagnetic radiation (photons of light) that have exactly the same energy as the difference in energy between the orbits jumped by the electron. For hydrogen, when an electron returns to the second orbital ($n = 2$) it emits a photon with energy that corresponds to a particular color or spectral line found in the Balmer series of lines located in the visible portion of the electromagnetic (light) spectrum. The particular color in the series depends on the higher orbital from which the electron jumped. When the electron returns all the way to the innermost orbital ($n = 1$), the photon emitted has more energy and forms a line in the Lyman series found in the higher energy, ultraviolet portion of the spectrum. When the electron returns to the third quantum shell ($n = 3$), it retains more energy and, therefore, the photon emitted is correspondingly lower in energy and forms a line in the Paschen series found in the lower energy, infrared portion of the spectrum.

Because electrons are moving charged particles, they also generate a **magnetic field**. Just as an ampere is a unit of electric current, a magneton is a unit of magnetic dipole moment. The orbital magnetic moment for hydrogen atom is called the Bohr magneton.

Bohr's work earned a Nobel Prize in 1922. Subsequently, more mathematically complex models based on the work of French physicist Louis Victor de Broglie (1892–1987) and Austrian physicist **Erwin Schrödinger** (1887–1961) that depicted the particle and wave nature of electrons proved more useful to describe atoms with more than one electron. The standard model incorporating quark particles further refines the Bohr model. Regardless, Bohr's model remains fundamental to the study of **chemistry**, especially the valence shell concept used to predict an element's reactive properties.

The Bohr model remains a landmark in scientific thought that poses profound questions for scientists and philosophers. The concept that electrons make quantum leaps from one orbit to another, as opposed to simply moving between orbits, seems counter-intuitive, that is, outside the human experience with nature. Bohr said, "Anyone who is not shocked by quantum theory has not understood it." Like much of quantum theory, the proofs of how nature works at the atomic level are mathematical.

See also Atomic mass and weight; Atomic number; Quantum electrodynamics (QED); Quantum theory and mechanics

BOHR, NIELS (1885-1962)

Danish physicist

Niels Bohr received the Nobel Prize in physics in 1922 for the quantum mechanical model of the **atom** that he had developed a decade earlier, the most significant step forward in scientific understanding of atomic structure since English physicist John Dalton first proposed the modern **atomic theory** in 1803. Bohr founded the Institute for Theoretical Physics at the University of Copenhagen in 1920, an Institute later renamed for him. For well over half a century, the Institute was a powerful force in the shaping of atomic theory. It was an essential stopover for all young physicists who made the tour of Europe's center of theoretical physics in the mid-twentieth century. Also during the 1920s, Bohr thought and wrote about some of the fundamental issues raised by modern **quantum theory**. He developed two basic concepts, the principles of complementarity and correspondence, both of which he held must direct all future work in physics. In the 1930s, Bohr became interested in problems of the atomic nucleus and contributed to the development of the liquid-drop model of the nucleus, a model used in the explanation of **nuclear fission**.

Niels Henrik David Bohr was born on in Copenhagen, Denmark, the second of three children of Christian and Ellen Adler Bohr. Bohr's early upbringing was enriched by a nurturing and supportive home atmosphere. His mother had come from a wealthy Jewish family involved in banking, government, and public service. Bohr's father was a professor of physiology at the University of Copenhagen. His closest friends met every Friday night to discuss events, and often, young Niels listened to the conversations during these gatherings.

Bohr became interested in science at an early age. His biographer, Ruth Moore, has written in her book *Niels Bohr: The Man, His Science, and the World They Changed* that as a child he "was already fixing the family clocks and anything else that needed repair." Bohr received his primary and secondary education at the Gammelholm School in Copenhagen. He did well in his studies, although he was apparently overshadowed by the work of his younger brother Harald, who later became a mathematician. Both brothers were also excellent soccer players.

On his graduation from high school in 1903, Bohr entered the University of Copenhagen, where he majored in physics. He soon distinguished himself with a noteworthy research project on the surface tension of **water** as evidenced in a vibrating **jet stream**. For this work, he was awarded a gold medal by the Royal Danish Academy of Science in 1907. In the same year, he was awarded his bachelor of science degree, to be followed two years later by a master of science degree. Bohr then stayed on at Copenhagen to work on his doctorate, which he gained in 1911. His doctoral thesis dealt with the electron theory of **metals** and confirmed the fact that classical physical principles were sufficiently accurate to describe the qualitative properties of metals but failed when applied to quantitative properties. Probably the main result of this research was to convince Bohr that classical electromagnetism could not satisfactorily describe atomic phenomena. The stage had been set for Bohr's attack on the most fundamental questions of atomic theory.

Bohr decided that the logical place to continue his research was at the Cavendish Laboratory at Cambridge University. The director of the laboratory at the time was English physicist J. J. Thomson, discoverer of the electron. Only a few months after arriving in England in 1911, however, Bohr discovered that Thomson had moved on to other topics and was not especially interested in Bohr's thesis or ideas. Fortunately, however, Bohr met English physicist Ernest Rutherford, then at the University of Manchester, and received a much more enthusiastic response. As a result, he moved to Manchester in 1912 and spent the remaining three months of his time in England working on Rutherford's nuclear model of the atom.

On July 24, 1912, Bohr boarded ship for his return to Copenhagen and a job as assistant professor of physics at the University of Copenhagen. Also waiting for him was his bride-to-be Margrethe Nørlund, whom he married on August 1. The couple later had six sons. One son, Aage, earned a share of the 1975 Nobel Prize in physics for his work on the structure of the atomic nucleus.

The field of atomic physics was going through a difficult phase in 1912. Rutherford had only recently discovered the atomic nucleus, which had created a profound problem for theorists. The existence of the nucleus meant that electrons must have been circling it in orbits somewhat similar to those traveled by planets in their motion around the **Sun**. According to classical laws of electrodynamics, however, an electrically charged particle would continuously radiate energy as it traveled in such an orbit around the nucleus. Over time, the electron would spiral ever closer to the nucleus and eventually collide with it. Although electrons clearly must be orbiting the nucleus, they could not be doing so according to classical laws.

Bohr arrived at a solution to this dilemma in a somewhat roundabout fashion. He began by considering the question of atomic spectra. For more than a century, scientists had known that the heating of an element produces a characteristic line spectrum; that is, the specific pattern of lines produced is unique for each specific element. Although a great deal of research had been done on spectral lines, no one had thought very deeply about what their relationship might be with atoms, the building blocks of elements.

When Bohr began to attack this question, he decided to pursue a line of research begun by the German physicist Johann Balmer in the 1880s. Balmer had found that the lines in the hydrogen spectrum could be represented by a relatively simple mathematical formula relating the frequency of a particular line to two integers whose significance Balmer could not explain. It was clear that the formula gave very precise values for line frequencies that corresponded well with those observed in experiments.

Niels Bohr. ***Library of Congress.***

When Bohr's attention was first attracted to this formula, he realized at once that he had the solution to the problem of electron orbits. The solution that Bohr worked out was both simple and elegant. In a brash display of hypothesizing, Bohr declared that certain orbits existed within an atom in which an electron could travel without radiating energy; that is, classical laws of physics were suspended within these orbits. The two integers in the Balmer formula, Bohr said, referred to orbit numbers of the "permitted" orbits, and the frequency of spectral lines corresponded to the energy released when an electron moved from one orbit to another.

Bohr's hypothesis was brash because he had essentially no theoretical basis for predicting the existence of "allowed" orbits. To be sure, German physicist Max Planck's quantum hypothesis of a decade earlier had provided some hint that Bohr's "quantification of space" might make sense, but the fundamental argument for accepting the hypothesis was simply that it worked. When his model was used to calculate a variety of atomic characteristics, it did so correctly. Although the hypothesis failed when applied to detailed features of atomic spectra, it worked well enough to earn the praise of many colleagues.

Bohr published his theory of the "planetary atom" in 1913. That paper included a section that provided an interesting and decisive addendum to his basic hypothesis. One of the apparent failures of the Bohr hypothesis was its seeming inability to predict a set of spectral lines known as the Pickering series, lines for which the two integers in the Balmer formula required half-integral values. According to Bohr, of course, no "half-orbits" could exist that would explain these values. Bohr's solution to this problem was to suggest that the Pickering series did not apply to hydrogen at all, but to helium atoms that had lost an electron. He rewrote the Balmer formula to reflect this condition.

Within a short period of time spectroscopists in England had studied samples of helium carefully purged of hydrogen and found Bohr's hypothesis to be correct. Although a number of physicists were still debating Bohr's theory, at least one—Rutherford—was convinced that the young Danish physicist was a highly promising researcher. He offered Bohr a post as lecturer in physics at Manchester, a job that Bohr eagerly accepted and held from 1914 to 1916. He then returned to the University of Copenhagen, where a chair of theoretical physics had been created specifically for him. Within a few years he was to become involved in the planning for and construction of the University of Copenhagen's new Institute for Theoretical Physics, of which he was to serve as director for the next four decades.

In many ways, Bohr's atomic theory marked a sharp break between classical physics and a revolutionary new approach to natural phenomena made necessary by quantum theory and relativity. He was very much concerned about how scientists could and should now view the physical world, particularly in view of the conflicts that arose between classical and modern laws and principles. During the 1920s and 1930s, Bohr wrote extensively about this issue, proposing along the way two concepts that he considered to be fundamental to the "new physics." The first was the principle of complementarity that says, in effect, that there may be more than one true and accurate way to view natural phenomena. The best example of this situation is the wave-particle duality discovered in the 1930s, when particles were found to have wavelike characteristics and waves to have particle-like properties. Bohr argued that the two parts of a duality may appear to be inconsistent or even in conflict and that one can use only one viewpoint at a time, but he pointed out that both are necessary to obtain a complete view of particles and waves.

The second principle, the correspondence principle, was intended to show how the laws of classical physics could be preserved in light of the new quantum physics. We may know that quantum mechanics and relativity are essential to an understanding of phenomena on the atomic scale, Bohr said, but any conclusion drawn from these principles must not conflict with observations of the real world that can be made on a macroscopic scale. That is, the conclusions drawn from theoretical studies must correspond to the world described by the laws of classical physics.

In the decade following the publication of his atomic theory, Bohr continued to work on the application of that theory to atoms with more than one electron. The original theory had dealt only with the simplest of all atoms, hydrogen, but it was clearly of some interest to see how that theory could be extended to higher elements. In March, 1922, Bohr published a summary of his conclusions in a paper entitled "The Structure of the Atoms and the Physical and Chemical Properties of the Elements." Eight months later, Bohr learned that he had been awarded the Nobel Prize in physics for his theory of atomic structure, by that time universally accepted among physicists.

During the 1930s, Bohr turned to a new, but related, topic: the composition of the atomic nucleus. By 1934, scientists had found that the nucleus consists of two kinds of particles, protons and neutrons, but they had relatively little idea how those particles are arranged within the nucleus and what its general shape was. Bohr theorized that the nucleus could be compared to a liquid drop. The forces that operate between protons and neutrons could be compared in some ways, he said, to the forces that operate between the molecules that make up a drop of liquid. In this respect, the nucleus is no more static than a droplet of water. Instead, Bohr suggested, the nucleus should be considered to be constantly oscillating and changing shape in response to its internal forces. The greatest success of the Bohr liquid-drop model was its later ability to explain the process of nuclear fission discovered by German chemist Otto Hahn, German chemist Fritz Strassmann, and Austrian physicist Lise Meitner in 1938.

Bohr continued to work at his Institute during the early years of World War II, devoting considerable effort to helping his colleagues escape from the dangers of Nazi Germany. When he received word in September 1943 that his own life was in danger, Bohr decided that he and his family would have to leave Denmark. The Bohrs were smuggled out of the country to Sweden aboard a fishing boat and then, a month later, flown to England in the empty bomb bay of a Mosquito bomber. The Bohrs then made their way to the United States, where both Bohr and his son became engaged in work on the Manhattan Project to build the world's first atomic bombs.

After the War, Bohr, like many other Manhattan Project researchers, became active in efforts to keep control of atomic weapons out of the hands of the military and under close civilian supervision. For his long-term efforts on behalf of the peaceful uses of atomic energy, Bohr received the first Atoms for Peace Award given by the Ford Foundation in 1957. Meanwhile, Bohr had returned to his Institute for Theoretical Physics and become involved in the creation of the European Center for Nuclear Research (CERN). He also took part in the founding of the Nordic Institute for Theoretical Atomic Physics (Nordita) in Copenhagen. Nordita was formed to further cooperation among and provide support for physicists from Norway, Sweden, Finland, Denmark, and Iceland.

Bohr reached the mandatory retirement age of seventy in 1955 and was required to leave his position as professor of physics at the University of Copenhagen. He continued to serve as director of the Institute for Theoretical Physics until his death in Copenhagen at the age of 77.

Bohr was held in enormous respect and esteem by his colleagues in the scientific community. American physicist **Albert Einstein**, for example, credited him with having a "rare blend of boldness and caution; seldom has anyone possessed such an intuitive grasp of hidden things combined with such a strong critical sense." Among the many awards Bohr received were the Max Planck Medal of the German Physical Society in

1930, the Hughes (1921) and Copley (1938) medals of the Royal Society, the Franklin Medal of the Franklin Institute in 1926, and the Faraday Medal of the Chemical Society of London in 1930. He was elected to more than twenty scientific academies around the world and was awarded honorary doctorates by a dozen universities, including Cambridge, Oxford, Manchester, Edinburgh, the Sorbonne, Harvard, and Princeton.

See also Bohr Model

BORA • *see* SEASONAL WINDS

BOULDER • *see* ROCK

BOWEN'S REACTION SERIES

Bowen's reaction series describes the formation of **minerals** as **magma** cools. Rocks formed from magma are **igneous rocks**, and minerals crystallize as magma cools. The **temperature** of the magma and the rate of cooling determine which minerals are stable (i.e., which minerals can form) and the size of the mineral **crystals** formed (i.e., texture). The slower a magma cools, the larger crystals can grow.

Named after geologist Norman L. Bowen (1887–1956), Bowen's reaction series allows geologists to predict chemical composition and texture based upon the temperature of a cooling magma.

Bowen's reaction series is usually diagramed as a "Y" with horizontal lines drawn across the "Y." The first horizontal line—usually placed just above the top of the "Y"—represents a temperature of 3,272°F (1,800°C). The next horizontal line, represents a temperature of 2,012°F (1,100°C) and is located one-third of the way between the top of the "Y" and the point where the two arms join the base. A third line representing a temperature of 1,652°F (900°C) is located two-thirds of the way from the top of the "Y" to juncture of the upper arms. A fourth horizontal line—representing a temperature of 1,112deg;F (600°C)—intersects the triple point junction where the upper arms of the "Y" meet the base portion.

The horizontal temperature lines divide the "Y" into four compositional sections. Mineral formation is not possible above 3,272°F (1,800°C). Between 2,012°F (1,100°C) and 3,272°F (1,800°C), rocks are ultramafic in composition. Between 1,652°F (900°C) and 2,012°F (1,100°C), rocks are **mafic** in composition. Between 1,112°F (600°C) and 1,652°F (900°C), rocks are intermediate in composition. Below 1,112°F (600°C), **felsic** rocks form.

The upper arms of the "Y" represent two different formation pathways. By convention, the left upper arm represents the discontinuous arm or pathway. The upper right arm represents the continuous arm or continuous path of formation. The discontinuous arm represents mineral formations rich in **iron** and magnesium. The first mineral to form is olivine—it is the only mineral stable at or just below 3,272°F (1,800°C). As the temperature decreases, pyroxene becomes stable. The general chemical compositional formula—used throughout this article and not to be confused with a balanced molecular or empirical chemical formula—at the highest temperatures includes iron, magnesium, **silicon,** and **oxygen** (FeMgSiO, but no **quartz**). At approximately 2,012°F (1,100°C), calcium containing minerals (CaFeMgSiO) become stable. As the temperature lowers to 1,652°F (900°C), amphibole (CaFeMgSiOOH) forms. As the magmas cools to 1,112°F (600°C), biotite (KFeMgSiOOH) formation is stable.

The continuous arm of Bowen's reaction series represents the formation of **feldspar** (**plagioclase**) in a continuous and gradual series that starts with calcium rich feldspar (Ca-feldspar, CaAlSiO) and continues with a gradual increase in the formation of sodium containing feldspar (Ca-Na-feldspar, CaNaAlSiO) until an equilibrium is established at approximately 1,652°F (900°C). As the magmas cool and the calcium ions are depleted, the feldspar formation becomes predominantly sodium feldspar (Na-feldspar, NaAlSiO). At 1,112°F (600°C), the feldspar formation is nearly 100% sodium feldspar (Na-feldspar, NaAlSiO).

At or just below 1,112°F (600°C), the upper arms of the "Y" join the base. At this point in the magma cooling, K-feldspar or orthoclase (KAlSiO) forms and as the temperature begins to cool further, muscovite (KAlSiOOH) becomes stable. Just above the base of the "Y," the temperature is just above the point where the magma completely solidifies. At these coolest depicted temperatures (just above 392°F [200°C]), quartz (SiO) forms.

The time that the magma is allowed to cool will then determine whether the **rock** will be **pegmatite** (produced by extremely slow cooling producing very large crystals), phaneritic (produced by slow cooling that produces visible crystals), **aphanitic** (intermediate cooling times that produce microscopic crystals), or glassy in texture (a product of rapid cooling without crystal formation). When magmas experience differential cooling conditions, they produce porphyritic rock, a mixture of crystal sizes and exhibit either a phaneritic or aphanitic groundmass.

Although the above temperature and percentage composition data are approximate, simplified (e.g., the formation of hornblende has been omitted), and idealized, Bowen's reaction series allows the prediction of mineral content in rock and, by examination of rock, allows the reverse determination of the conditions under which the magma cooled and igneous rock formed.

See also Chemical bonds and physical properties; Crystals and crystallography; Magma chamber; Mineralogy; Rate factors in geologic processes; Temperature and temperature scales

BRAHE, TYCHO (1546-1601)

Danish astronomer

Tycho Brahe was one of the most colorful astronomers in history. Born in Denmark, Brahe was "adopted" (some say kidnapped) by his childless uncle at the age of one. Either way, his father, a Swedish nobleman, did not pursue the matter

Tycho Brahe. ***New York Public Library Picture Collection.***

(Brahe's given name was "Tyge," but the Latinized version is more common.)

Brahe received an excellent education. At the age of 13 he entered the University of Copenhagen, where he studied rhetoric and philosophy. He was well on his way toward a career in politics when he witnessed an **eclipse** of the **Sun** on August 21, 1560. Brahe spent the next two years studying mathematics and **astronomy**. He moved on to the University of Leipzig in 1562 where a tutor tried to influence him to study law, but Brahe refused to be diverted.

In August 1563, he made his first recorded observation, a close grouping between Jupiter and Saturn. (It was not until many years that Galileo first used a **telescope** to make astronomical observations; Brahe's precise work was done with the naked eye.) This was the turning point of his career. He was perturbed to note that this event occurred a month before its predicted date, and he began to buy astronomical instruments that would allow him to make very precise measurements so he could produce more accurate tables of data. He also developed interests in alchemy and astrology (which he considered a science) and began to cast horoscopes that, if nothing else, generated some income.

In November 1572, a supernova burst into view in the constellation of Cassiopeia, and Brahe was enthralled. The new star became brighter than Venus and was visible for eighteen months. He described it (along with its astrological "significance") with such detail in a book, the new star became known as "Tycho's star."

The book did three things: the title *De Nova Stella* (Concerning the new star) linked the name nova to all exploding stars. In addition, Brahe had been unable to make a parallax measurement for the nova. That indicated that it was much more distant than the **Moon**, which was a crushing blow to Aristotle's teachings that the heavens were perfect and unchanging. The third accomplishment was in establishing Brahe's reputation as an astronomer. The book was almost not produced. Initially, Brahe felt it was beneath his dignity as a nobleman to publish, but he was soon convinced otherwise.

Brahe's arrogance was legendary. At the age of nineteen, he was involved in a duel over a mathematical point, during which he lost his nose. He spent the rest of his life wearing a prosthesis. Fortunately, one of the few individuals not alienated by Brahe was Frederick II, the king of Denmark. In 1576, this patron of science gave Brahe a small island called Hveen, subsidized the building of an observatory there, and endowed Brahe with an annual payment. This became the first real astronomical observatory in history, and Brahe, always mindful of his noble background, saw to it that no expense was spared. The principal building, *Uraniborg* (Castle of the heavens), was the main residence; next to it was built the main observatory, *Stjerneborg* (Castle of the stars).

In 1577, a bright comet was visible, and Brahe observed it with great care. Measurements showed that it, too, was further than the moon and could not be atmospheric phenomena as Aristotle taught. Worse, Brahe reluctantly came to the conclusion that the path of the comet was not circular but elongated. This meant it would have to pass through the "spheres" that carried the planets around the sky, which would be impossible unless the spheres did not exist.

This concept troubled Brahe, who rejected the Sun-centered theory of Nicholas Copernicus because it not only violated scripture, it contradicted the teachings of **Ptolemy**. Brahe also reasoned that if Copernican theory was correct, he should have been able to detect stellar parallax as the year passed, but he could not.

Brahe tried to reconcile his beliefs with his observations by proposing a **solar system** in which all the planets orbited around the Sun, but the Sun orbited around the earth (to account for a year), and the celestial sphere made a single **rotation** each day. This would follow Copernicus's theory, do away with the Greeks' planetary spheres, and still keep the earth at its preeminent position. The Tychonic Theory was almost entirely ignored.

Brahe spent 20 years at Hveen, making exceptionally accurate observations. He used devices such as a huge quadrant with a radius of 6 feet (1.83 m), sextants, a bipartite arc, astrolabes, and various armillae. His measurements were the most precise that could be made without the aid of a telescope. He made corrections for nearly every known astronomical measurement and made Pope Gregory's calendar reform in 1582 possible. (Brahe himself did not adopt the new calendar until 1599.)

Frederick II died in 1588. His son, Christian IV, was only 11, so the country was ruled by regents, who left Brahe to his own devices. When Christian came of age in 1596, he quickly lost patience with the expensive, haughty astronomer, and Brahe was relieved of his royal duties the following year.

Brahe moved to Prague, where he resumed observing. As an assistant he employed a young German named **Johannes Kepler**, to whom he gave all his observations on Mars and the task of preparing tables of planetary motion. This would turn out to be the most significant decision of his life, as Kepler used the data to determine the elliptical nature of planetary motion.

BRAUN, WERNHER VON (1912-1977)

German-born American aerospace engineer

Wernher von Braun was the most famous rocket engineer of his time, noted promoter of **space** flight. Teams under his direction designed the V–2, Redstone, Jupiter, and Pershing missiles, as well as the Jupiter C, Juno, and Saturn launch vehicles that carried most of the early U.S. satellites and spacecraft beyond the earth's atmosphere and ultimately to the **moon**. He became both a celebrity and a national hero in the United States, winning numerous awards, including the first **Robert H. Goddard** Memorial Trophy in 1958, the Distinguished Federal Civilian Service Award (presented by President Dwight D. Eisenhower) in 1959, and the National Medal of Science in 1977. As President Jimmy Carter stated at the time of his death: "To millions of Americans, [his] name was inextricably linked to our exploration of space and to the creative application of technology. He was not only a skillful engineer but also a man of bold vision; his inspirational leadership helped mobilize and maintain the effort we needed to reach the Moon and beyond."

The second of three children (all male), Wernher Magnus Maximilian von Braun was born in the east German town of Wirsitz (later, Wyrzysk, Poland). He was the son of Baron Magnus Alexander Maximilian von Braun—then the principal magistrate (*Landrat*) of the governmental district and later (1932–early 1933) the minister of nutrition and agriculture in the last two governments of the Weimar Republic before Hitler rose to power in Germany—and of Emmy (von Quistorp) von Braun, a well-educated woman from the Swedish-German aristocracy with a strong interest in biology and **astronomy**. She inspired her son's interest in space flight by supplying him with the science fiction works of Jules Verne and H. G. Wells and by giving him a **telescope** as a gift upon his confirmation into the Lutheran church in his early teens, instead of the customary watch or camera. Despite these influences, the young von Braun was initially a weak student and was held back one year in secondary school because of his inability in math and **physics**. Due to his interest in astronomy and rockets, he obtained a copy of space pioneer Hermann Oberth's book *Die Rakete zu den Planeträumen* ("Rockets to planetary space") in 1925. Appalled that he could not understand its complicated mathematical formulas, he determined to master his two weakest subjects. Upon completion of secondary school, von Braun entered the Berlin-Charlottenburg Institute of Technology, where he earned a bachelor of science in mechanical engineering and aircraft construction in 1932.

Wernher von Braun. *Library of Congress.*

In the spring of 1930, von Braun found time to work as part of the German Society for Space Travel, a group founded in part by Hermann Oberth which experimented with small, liquid-fueled rockets. Although Oberth returned to a teaching position in his native Romania, von Braun continued working with the society. When the group ran short of funds during the Depression, von Braun, then twenty, reluctantly accepted the sponsorship of the German military. In 1932 he went to work for the German army's ordnance department at Kummersdorf near Berlin, continuing to develop liquid-fueled rockets. Entering the University of Berlin about this same time, he used his work at Kummersdorf as the basis for his doctoral dissertation and received his Ph.D. in physics in 1934.

Von Braun's staff at Kummersdorf eventually grew to some eighty people, and in early 1937, the group moved to Peenemünde, a town on the Baltic coast where the German army together with the air force had constructed new facilities. Before the move, engineers at Kummersdorf had begun developing ever-larger rockets, and in 1936 they completed the preliminary design for the A–4, better known as the V–2. This was an exceptionally ambitious undertaking, since the missile was to be 45 feet long, deliver a 1-ton warhead to a target some 160 miles distant, and employ a rocket motor that could deliver a 25-ton thrust for 60 seconds, compared to the 1.5 tons of thrust supplied by the largest liquid-fueled rocket motors then available. Von Braun's team encountered numerous difficulties—perfecting the injection system for the propellants, mastering the aerodynamic properties of the missile, and especially in developing its guidance and control system. Thus, even with the assistance of private industry and universities, the first successful launch of the A–4 did not occur at Peenemünde until October 3, 1942. Despite this success, failed launches continued to plague the project, and as a result the first fully operational V–2s were not fired until September 1944. Between then and the end of the war, approximately 6,000 rockets were manufactured at an underground production site named *Mittelwerk*, using the slave labor of concentration camp inmates and prisoners of war. Although several thousand V–2s struck London, Antwerp, and other allied targets, they were not strategically significant in the German war effort. Their importance lies in the technological advances they brought to the development of rocketry.

As the war drew to a close in **Europe** in the early months of 1945, von Braun organized the move of hundreds of people from Peenemünde to Bavaria so they could surrender to the Americans rather than the Soviets. Subsequently, about 120 of them went to Fort Bliss near El Paso, Texas, as part of a military operation called Project Paperclip. They worked on rocket development and employed captured V–2s for high altitude research at the nearby White Sands Proving Ground in New Mexico. In the midst of these efforts, von Braun returned to Germany to marry, returning with his wife to Texas after the wedding. In 1950, the von Braun team transferred to the Redstone Arsenal near Huntsville, Alabama, where between April 1950 and February 1956, it developed the Redstone medium-range ballistic missile under his technical direction. Deployed in 1958, the Redstone was basically an offshoot of the V–2 but featured several modifications including an improved inertial guidance system. The Redstone also served as a launch vehicle, placing Alan B. Shephard and Virgil I. "Gus" Grissom in suborbital flight in May and July 1961, respectively. Meanwhile, in February 1956, von Braun became the director of the development operations division of the newly established Army Ballistic Missile Agency (ABMA) in Huntsville. While located there, he and his wife raised three children. Von Braun himself became a U.S. citizen on April 14, 1955.

Undoubtedly the greatest claim to fame of von Braun and his team was the powerful Saturn family of rockets, which propelled Americans into lunar orbit and landed 12 of them on the moon between July 1969 and January 1971. Development of these launch vehicles began under ABMA and was completed during the decade after July 1, 1960, when von Braun and over 4,000 ABMA personnel transferred to the National Aeronautics and Space Administration (NASA), forming the George C. Marshall Space Flight Center, which von Braun directed until February 1970. The Saturn I and Ib were developmental rockets leading to the massive Saturn V that actually launched the astronauts of the Apollo program. Propelled by liquid **oxygen** and kerosene in its first stage, liquid oxygen and liquid hydrogen for the two upper stages, the Saturn V stood 363 feet high, six stories above the level of the Statue of Liberty. Its first stage constituted the largest **aluminum** cylinder ever produced; its valves were as large as barrels, its fuel pumps larger than refrigerators.

As von Braun repeatedly insisted, he and his team were not alone responsible for the success of the Saturn and Apollo programs. In fact, the engineers at Marshall often urged more conservative solutions to problems occurring in both programs than NASA ultimately adopted. To von Braun's credit, he invariably accepted and supported the more radical approaches once he was convinced they were right. One example involved the debate over all-up versus step-by-step testing of Saturn V. Having experienced numerous rocket system failures going back to the V–2 and beyond, the German engineers favored testing each stage of the complicated rocket. At NASA headquarters, however, administrator George Mueller preferred the Air Force approach, which relied much more heavily on ground testing. He therefore insisted upon testing Saturn V all at once in order to meet President John F. Kennedy's ambitious goal of landing an American on the moon before the end of the decade. Ever cautious, von Braun hesitated but finally concurred in the ultimately successful procedure.

Beyond his role as an engineer, scientist, and project manager, von Braun was also an important advocate for space flight, publishing numerous books and magazine articles, serving as a consultant for television programs and films as well as testifying before Congress. Perhaps most important in this regard were his contributions, with others, to a series of *Collier's* articles from 1952 to 1953 and to a Walt Disney television series produced by Ward Kimball from 1955 to 1957. Both series were enormously influential and, along with the fears aroused by the Soviet space program, galvanized American efforts to conquer space.

See also History of manned space exploration; Spacecraft, manned

BRECCIA

Breccias are rocks composed of angular clasts (fragments). In monomictic breccias, clasts have the same composition, whereas polymictic breccias contain clasts of different compositions. Sedimentary breccias comprise more than 30% gravel-size (>2mm) angular clasts produced by mechanical **weathering** or brittle deformation of nearby rocks. Their angular shape implies minimal transport. Sedimentary breccias develop at the base of talus slopes or in proximity to active faults. Karst breccia forms during **erosion**, dissolution and collapse of **limestone**. Pressure solution due to high local stresses at contacts between angular fragments of limestone, **marble**, or **chert** can result in interpenetration of clasts. Breccias can form during the emplacement of igneous bodies by explosive exsolution of volatile phases and/or explosive interaction of **magma** with **groundwater**. Intrusive breccias (such as associated with kimberlite pipes) often contain fragments of both intrusive and host rocks. Igneous breccia dykes may contain a wide range of **rock** fragments sampled during magma ascent and thus, provide information about the composition of rocks at deeper levels. Volcanic breccias containing lithic (rock) and vitric (**glass** and **pumice**) fragments form near subaerial volcanic vents.

Fault brecciation (or tectonic comminution) can occur due to the development and linkage of a network of fractures during faulting in the upper **crust**. The size of breccia fragments is highly variable. Milling or wear abrasion during displacement on faults may result in further brecciation and size reduction. Fracturing occurs when the applied stress exceeds the brittle resistance of the material or by transient elevation of fluid pressure (hydraulic or fluid-assisted brecciation). The interaction of hydrothermal fluids with tectonically brecciated rock produces hydrothermal breccias common in ore deposits. Brecciation may also occur due to implosion of a vein resulting from a sudden decrease in pressure (critical fracturing) in response to a sudden opening of **space** generated by rapid slip or intersection between different veins. When fault slip is extremely rapid, melt generated by frictional heating is injected along fractures to produce veins of black glass (pseudotachylite) surrounding angular fragments of the surrounding rock.

Impact melt-breccias form by the fracturing and fusion of rocks under extreme pressures and temperatures rapidly induced during meteorite impacts. Impact melt-breccias contain partially or completely melted clasts of basement rocks within a cryptocrystalline glass, **feldspar** and calcium-pyroxene-rich matrix. Impact-melt breccias containing clastic debris and glass fragments produced by meteorite bombardment have been collected from the surface of the **Moon** during Apollo missions.

BUFFON, GEORGES-LOUIS LECLERC, COMTE DE (1707-1788)

French naturalist

Georges Louis Leclerc, Comte de Buffon was an eighteenth century naturalist who advocated the idea that natural forces worked to shape Earth in a gradual and ongoing process. By rejecting the widely-held notion of his time that Earth was shaped by catastrophic divine acts, Buffon inspired later geologists and naturalists to investigate and define the process of natural **evolution**.

Buffon was born to an aristocratic family in Montbard, France. His affluent background allowed him to travel extensively and pursue a number of fields before he developed a passionate interest in natural history. After studying at the Jesuit College in Dijon, France, Buffon obtained a law degree in 1726. The intellectual life of Dijon was active but not oriented toward science, so Buffon went off to Angers, a city in northwestern France, to study medicine, mathematics, botany, and **astronomy**. The threat of a duel forced him to leave Angers in 1730, but he seized the opportunity to travel through France, England, and Italy. While he was traveling, Buffon's mother died and left him a sizable fortune.

Buffon had been so impressed with the upsurge of science in England that he dedicated the next couple of years to scientific endeavors. His first project, at the request of the French navy, was to write about the tensile strength of timber so that the government could improve the construction of war vessels. Next, he undertook a study of probability theory, *Mémoire sur le jeu du franc-carreau,* a project that contributed to his election to the Royal Society in 1730 and his admission to the Académie Royale des Sciences in 1734.

Buffon began to take an interest in botany and forestry. He wrote numerous dissertations and translated several works into French, including Stephen Hales' works on plants, *Vegetable Statiks*, and Isaac Newton's work on calculus. By this time, his work in the sciences began to elevate his standing, and he was advanced and transferred from the mechanical to the botanical section of the Académie Royale.

Nevertheless, Buffon's interest in natural history remained casual until he was appointed to the prestigious position of keeper of the Jardin du Roi, the French botanical gardens. This opportunity enabled him, for the next 50 years, to spend summers at the estate and return to Paris for the winters. During this time, he published 44 volumes of his *Historie Naturelle* (Natural history), famous as the first modern work that attempted to treat nature as a whole. It was essentially the first encyclopedia on natural history to encompass both plant and animal kingdoms. Assisted by several eminent naturalists of the time, Buffon organized the often-confusing wealth of material into a coherent form. Moreover, in the work, he included suggestions on how the earth might have originated, and he challenged the then-popular belief that the earth was only 6,000 years old. Besides proposing that the earth might be much older, he also suggested that the fact that animals retain parts that serve no known purpose to them is evidence that animals have evolved.

Buffon's popularity increased dramatically due to this work, and he remained a well-known scientific figure until his death in 1788. His prestige earned him an invitation to become a member of many academic societies, including those in Berlin, Germany, and St. Petersburg, Russia. Members of the aristocracy bestowed gifts upon Buffon and King Louis XV made him a count, commissioning a famous sculptor to create a bust of him.

See also Evolution, evidence of; Evolutionary mechanisms

BUTTE • *see* LANDFORMS

BUTTERFLY EFFECT • *see* CHAOS THEORY (METEOROLOGICAL ASPECTS)

C

CALCAREOUS OOZE

Calcareous ooze is the general term for layers of muddy, calcium carbonate ($CaCO_3$) bearing soft **rock** sediment on the seafloor. Of all the distinct types of veneers covering the Earth's crust—be it **soil**, sediment, snow, or ice—none are more widespread than red-clay and calcareous ooze. Only a small proportion of calcareous ooze is precipitated inorganically. For the most part, calcareous ooze comprises the fossil hard parts of planktic (Greek *planktos* = floating around) and benthic (Greek *benthos* = the deep) single-celled marine organisms whose calcium carbonate skeletons are discarded upon death or reproduction. Calcareous ooze is distinguished by its main biogenic component into foraminiferal ooze, coccolithophore ooze, or pteropod ooze, respectively. However, coccolithophorids and planktic foraminifera form the largest part of the pelagic calcareous ooze with less contribution due to pteropods, calcareous dinoflagellates, and lithothamnium.

Foraminiferal ooze contains foraminifera (in Latin, *foramen* = hole; *ferre* = bearing), large, mainly marine protozoans that bear a shell perforated with small holes through which temporary cytoplasmic protrusions (pseudopodia) project. Foraminifera are divided into planktic and benthic foraminifera that inhabit the upper few hundred meters or the bottom of the world **oceans**, respectively. Their global distribution through passive transport by ocean currents, coupled with their prolific productivity and sensitivity to environmental variations, has led to their utilization for interpreting marine sediments. Despite their low number of modern species, their vast quantities produce a sediment cover that occupies roughly one third of the entire earth's surface.

Coccolithophorid ooze contains coccolithophorids (in Greek, *kokkos* = grain; *lithos* = stone; *phoros* = bearing), belong to marine nanno-phytoplankton (algae) whose cells (the so-called coccospheres) are covered by calcite platelets (the so-called coccoliths). However, the ratio of coccoliths per cell varies for different species. Coccolithophorids live in all oceans and depending on geographical zonation, species dominance is changing. Ecological strategies are likely to enable certain species to adapt to different **temperature**, nutrient, light, or energy regimes. Once dead, coccolithophorids disintegrate into single coccoliths that lastly are preserved as coccolith (ophorid) ooze. Coccolithophorids (and even more their coccoliths) may be small in size, but they occur in huge numbers in the sediment.

Pteropod ooze contains pteropods (in Greek *pteron* = wing; *pod* = foot), marine gastropod mollusks adapted to pelagic life that have a foot with wing-shaped lobes used as swimming organs. They are abundant in all oceans, although most species seem to prefer the circum-global tropical and subtropical regions. Distribution of pteropods is limited by **water** depth, temperature, salinity, **oxygen** content, and nutrient supply. They form very thin and fragile shells that hardly preserve under biochemical (e.g., dissolution) or physical (e.g., ingestion) attack. For this reason, preservation of pteropod ooze is mostly restricted to shallow parts of the oceans, i.e., **continental shelf**, slopes, ridges and rises.

Calcium carbonate consists of calcium (Ca^{2+}), inorganic **carbon** (C^{4+}), and oxygen (O^{2-}) ions. Calcium ions are derived from **weathering** of continental calcareous hard rocks and are available in excess. In marine **geochemistry**, carbonate is expressed as total dissolved inorganic carbon and carbonate alkalinity. However, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions are the predominant forms of dissolved CO_2 in sea water. The simplified calcification reaction:

$$2\ HCO_3^- + Ca^{2+} \leftrightharpoons CaCO_3 + CO_2 + H_2O$$

shows that dissolved inorganic carbon (and carbonate alkalinity) lower while, in turn, CO_2 is released to the atmosphere. Consequently, $CaCO_3$ **precipitation** by marine organisms acts as one source for CO_2. Depending on the mineral structure, $CaCO_3$ is called calcite (trigonal structure) or aragonite (rhombic structure).

Due to a complex carbonate **chemistry**, calcareous ooze begins to dissolve below the calcium carbonate lysocline in the water column. Below the calcium carbonate compensation depth (**CCD**) calcareous ooze is completely dissolved.

$CaCO_3$-bearing hard parts carry unique geochemical signals, namely the naturally fractionated isotopes of the elements oxygen (i.e., ^{16}O, ^{18}O) and carbon (i.e., ^{12}C, ^{13}C, ^{14}C). In carbonated water, oxygen and carbon in the dissolved CO_2 and in the surrounding water exchange until there are set amounts of each isotope (^{16}O:^{18}O and ^{12}C:^{13}C:^{14}C, respectively) in CO_2 and H_2O. These amounts are determined by the bonding properties of each molecule type for each isotope, and are a function of temperature. The ^{16}O:^{18}O ratio gets higher the colder the water is from which it precipitates. Since marine organisms use ambient HCO_3^- and CO_3^{2-} ions to build their hard parts, we have knowledge of the isotopic composition of total CO_2 in sea water by measuring CO_2 in calcium carbonate precipitates.

The discovery of calcareous ooze in the deep-sea during the *H.M.S. Challenger* expedition (1872–76) stimulated crucial modern **climate** research. Calcareous ooze became a reliable recorder of past environmental conditions on Earth containing information on ancient **biosphere**, hydrosphere, and atmosphere properties. Among them are abundance and distribution patterns of organism assemblages, oxygen and carbon isotope signatures of calcareous hard parts, bulk sediment properties, etc. (the so-called proxy parameters). Past ocean characteristics (temperature, productivity, etc.) can therefore be deduced by determining the different proxies for any chosen sample. A set of consecutively dated samples (e.g., **chronostratigraphy** by means of ^{14}C, Rb/Sr, K/Ar) consequently yields time series of fossil records that can be transformed into successions of environmental conditions.

Investigating calcareous ooze of modern (i.e., Holocene) and ancient (e.g., Pleistocene) oceans means to elucidate the role that oceanic processes play in global climate change during various **geologic time** intervals and at different levels of precision. Among them, the global carbon cycle is one of the topics that many scientific disciplines have turned their attention to, since short and long term variations of CO_2 in the atmosphere can be attributed—at least partially—to fossil fuel emissions and other human activities.

These calcareous sediment records also contain information relating to the history of adjacent land masses, providing insight into the history of climate and vegetation cover on the continents.

See also Dating methods; Limestone

CALDERA

A caldera is a large, usually circular depression at the summit of a **volcano**. Most calderas are formed by subsidence or sinking of the central part of the volcano; a rare few are excavated by violent explosions.

Craters and calderas are distinct structures. Both are circular depressions at the tops of volcanoes, but a crater is much smaller than a caldera and is formed by the building up of material around a vent rather than by the subsidence of material below a cone.

A volcano's summit may subside in two ways. First, eruptions of large volumes of **pumice** or **magma**, or subterranean drainage of the latter to other areas, may empty a chamber beneath the volcano into which a portion of the cone collapses. Second, the summit of the volcano may act as a thin roof over a large **magma chamber** that breaks under its own weight and sinks, partly or wholly, into the magma beneath. The term cauldron is sometimes reserved for calderas formed by the foundering of a cone summit in underlying magma.

The largest volcanic structures in the world are resurgent calderas. Resurgent calderas form following intense **volcanic eruptions** comparable in violence to asteroid impacts. (None has occurred during historical times.) During such an eruption, vast ejections of volcanic material—in some cases, thousands of cubic miles of pumice and ash—excavate very wide underground chambers, much wider than the volcano itself. Large calderas, up to hundreds of square miles in extent, collapse into these chambers. After settling, the caldera floor resurges or bulges up again, lifted by the refilling magma chamber below. Is in the case of the 22 mile (35 km) wide Cerro Galan caldera in Argentina, which is visible as a whole only from orbit, resurgence has raised the center of the caldera to almost a mile (1500 m) above the point of lowest subsidence.

Caldera complexes—overlapping calderas, some swallowing parts of others—are sometimes formed by repeated episodes of partial subsidence. Calderas and caldera complexes are common not only on Earth but on other bodies in the **Solar System** where volcanoes have erupted in the past or are presently erupting, including Mars, Venus, and Io.

See also Silicic

CALICHE

Caliche and calcrete are obsolete terms for well-developed calcic horizons that are common to soils in arid and semi-arid areas, and which are now known to **soil** scientists and geomorphologists as Bk or K horizons. Caliche is also a colloquial term that has many different uses among miners in Spanish speaking countries.

Calcic horizons form by the gradual **precipitation** of calcium carbonate ($CaCO_3$) and, to a lesser extent, magnesium carbonate ($MgCO_3$) within the B horizon of a soil and follow several well-documented stages of development ranging from I to VI. Stage I calcic soil horizons consist of partial carbonate coatings over the bottoms of gravel particles in the B horizons of coarse grained soils and thin carbonate filaments in the B horizons of fine grained soils. By stage III, carbonate is continuous throughout the zone of accumulation, and the zone of carbonate accumulation is known as the K horizon. Stages IV through VI are characterized be complete carbonate cementation of the former soil and, ultimately, brecciation. These most highly developed calcic horizons are sometimes referred to as petrocalcic because of their rock-like nature, and often form cap rocks atop bluffs and escarpments in arid to semi-arid regions such as the southwestern United States.

The primary source of carbonate in calcic soils is atmospheric, both as carbonate rich dust and rainwater that percolates through the soils carrying dissolved bicarbonate ions. In rare cases, calcic horizons can be formed by other processes such as the upward wicking of carbonate-rich **water** from shallow water tables. Gypsic or halic soils are formed in arid environments when **gypsum** ($CaSO_4 \cdot H_2O$) or halite (NaCL) are precipitated instead of carbonates.

Rates of soil development are controlled by many factors, so universal conclusions about the time required to form calcic soil horizons cannot be drawn. Studies in southern New Mexico have shown, however, that Stage I calcic soils can be hundreds to thousands of years old, State II calcic soils can be thousands to tens of thousands of years old, and Stage III and higher calcic soils can be tens to hundreds of thousands of years old.

See also Breccia; Desert and desertification; Limestone; Soil and soil horizons

CALIFORNIA CURRENT • *see* OCEAN CIRCULATION AND CURRENTS

CALVING OF GLACIERS • *see* GLACIATION

CAMBRIAN PERIOD

Cambrian is the name given to a period of time in Earth's history (i.e., Cambrian Period), which spanned 570–510 million years ago. The proper name Cambrian is also given to all the rocks that formed during that time (i.e., Cambrian System). In other words, the Cambrian System is the **rock** record of events that occurred—and organisms that lived—during an interval of geological time called Cambrian Period. Cambrian is the initial period of the **Paleozoic Era**.

Cambrian is a name derived from the Roman name for Wales, which was *Cambria*. Wales was the original study location for sedimentary rock formed during this interval of Earth history. The term Cambrian was first used in 1835 by Professor Adam Sedgwick (1785–1873) of Cambridge University, who was studying the lower part of what was then called Transition strata (the oldest known **sedimentary rocks**) in Wales. Sedgwick was working in the same general **area** as another prominent stratigrapher of the day, Roderick Merchison (1792–1871), whose focus was upon the overlying Silurian System. Merchison eventually showed that there was some overlap in the original concept of Sedgwick's Cambrian System and his own Silurian System, and ultimately advocated (c. 1852) that the Cambrian System was in fact part of the Silurian. It was not until a comprehensive study of the Cambrian-Silurian overlap problem produced the intervening Ordovician System (1879), that the Cambrian System was fully accepted by all geologists. Since their recognition and definition during the nineteenth century, Cambrian strata have been mapped on all the world's continents.

During Cambrian, the breakup of the supercontinent of Gondwana began with the separation of some landmasses including part of **Asia** and the ancient continents called Baltica and Laurentia (i.e., proto-North America). During its separation from the main Gondwana land mass, Laurentia had a collision with the southern end of what is now **South America** (specifically western Argentina), which resulted in some crustal deformation and mountain building. At this time, there was essentially a single world ocean, which is referred to as Panthalassa.

During most of Cambrian, global sea levels were at relatively high elevations as compared with most of the balance of Earth's history. The world's continents were mainly low-lying deserts and alluvial plains, and the rising Cambrian sea—in what is known as the Sauk transgression—encroached upon these areas, thus forming vast epicontinental **seas**. For example, during most of Cambrian, sea level was so high that an epicontinental sea covered **North America** except for a series of low islands running southwest-northeast along the elevated middle part of the continent (i.e., the Transcontinental Arch) and some parts of the low-lying Canadian cratonic shield region.

Cambrian was a time of rising global temperatures and Cambrian global **climate** ultimately became warmer than today. During Cambrian, there were essentially no polar or high-altitude **glaciers**. Further, there were no continents located at polar positions. The Cambrian Earth likely had more equitable climates than present because of the large amount of surficial seawater (approximately 85% or more, compared to approximately 70 % at present) and lack of significant topographic **relief**. Winds were likely confined to rather well-defined belts, and there is good evidence of persistent trade winds preserved in vast cross-bedded Cambrian sandstones.

Cambrian life in the **oceans** was very plentiful, but rather primitive by modern standards. The transition of pre-Cambrian life forms (mainly soft-body impressions in rock) to Cambrian life (shell-bearing **fossils** and other fossils with hard parts) has been referred to as the "Cambrian explosion." This explosion is more apparent than real, as the main change was the advent of preservable hard parts and shells, which seem to suddenly appear at a level near the onset of Cambrian **sedimentation**. Cambrian faunas include some very unusual creatures that may represent extinct phyla of organisms or organisms so primitive that they are not easily assigned to extant phyla. The most famous of fossil localities with such Cambrian fossils is at Mount Wapta, British Columbia, Canada (i.e., Burgess Shale outcrops). In these strata, the earliest known chordate (spinal cord-bearing animal), *Pikaia*, was first found. Other marine creatures of Cambrian seas included the archaeocyathids and stromatoporoids (two extinct, sponge-like organisms that formed reefs), primitive sponges and corals, simple pelecypods and brachiopods (two kinds of bivalves), simple molluscs, primitive echinoderms and jawless fishes, nautiloids, and a diverse group of early arthropods (including many species of trilobites). Trilobites were particularly abundant and diverse, and over 600 genera of Cambrian trilobites are known. Some species of trilobites were the first organisms to develop complex eye structures. Numerous Cambrian reefs, patch reefs, and shallow-water mounds were formed by stromatolites, a layered mass of sediment formed by the daily trapping and binding action of a symbiotic growth of blue-green algae and bacteria.

Cambrian life on land was probably quite limited. There is evidence that stromatolitic growth of blue-green algae and bacteria covered rocks and formed sediment layers at or near oceanic shorelines and lake margins. However, complex life forms are not found in Cambrian terrestrial sediments. It is possible that some arthropods may have lived partially or entirely upon land at this time, but this is speculative in the absence of fossil evidence. There were no land plants at this time, and thus Cambrian landscapes were at the mercy of **wind** and **water erosion** without any protection from vegetation. The minimal level of photosynthetic activity before and during Cambrian raised **oxygen** levels in Earth's atmosphere to approximately 10% of that found in the modern atmosphere.

The end of Cambrian came gradually with falling sea levels and the onset of slightly cooler global temperatures. During Late Cambrian, trilobite species became the first organisms known to experience widespread mass extinction. In several events during Late Cambrian, trilobite faunas were wiped out over vast areas for causes that are not completely understood. Reasons proposed for the mass extinctions include competition with other organisms and rapid shifts in global **temperature** and/or sea-level changes. Trilobites persisted into Late Paleozoic, but not as prominently as they did in Cambrian seas. Ordovician succeeded Cambrian life and conditions. During Ordovician, plant and animal life continued to diversify, tectonic activity began to be more extensive, and global climate change became more intensive.

See also Stratigraphy; Supercontinents

CANNON, ANNIE JUMP (1863-1941)

American astronomer

Annie Jump Cannon developed a stellar classification system that is considered by many astronomers to be the foundation of stellar **spectroscopy**. The science of stellar spectroscopy analyzes the photographic spectrum of a star. The spectrum, a series of colors that can range from violet to red depending on the star's **temperature**, is produced by using a **telescope** to collect a star's light and to pass it through a spectroscope. The same effect occurs when sunlight passes through raindrops to produce a **rainbow**. The spectroscope also produces a series of narrow dark lines within the spectrum known as spectral lines. These lines give further clues to a star's temperature as well as composition, motion, and other information. Because the position of the spectral lines on the spectrum may vary greatly from one star to another, scientists sometimes refer to this spectrographic data as the fingerprint of a star and consider this information crucial to all stellar theories.

In devising her classification system, Cannon recognized the atmospheric temperature of a star as the most important of the various factors that determine the intensity of a star's spectral lines. Her method classified stars from hottest to coolest using capital letters to designate each major type of star. The letters O, B, A, F, G, K, and M represent the seven major categories. Cannon identified further distinctions within a major category by placing a number from zero to nine after each letter. For example, the **Sun** is a G–2 star.

Born in Dover, Delaware, Annie Jump Cannon was encouraged by her mother in the study of **astronomy** from an early age. Later, under the tutelage of two American astronomers, Wellesley professor Sarah Frances Whiting (1846–1927) and the Harvard College Observatory director Edward C. Pickering (1846–1919), Cannon became an expert in the relatively new field of astronomical spectroscopy.

It was Pickering who hired Cannon, along with a number of other women astronomers, to collect and catalog spectrographic data about the stars. Before attempting this enormous project, the astronomers needed a system by which hundreds of thousands of stars could be easily classified. Prior to Cannon's arrival at Harvard two other American astronomers, Wilamina Fleming (1857–1911) and Antonia Maury (1866–1952), had joined Pickering in devising two different classification systems. However, Pickering deemed both systems to be too complex or theoretical. Cannon borrowed from these earlier attempts in developing her own unique system of classification. Using her system, Cannon and her colleagues were able to classify the spectrum of over 300,000 stars. This information was published in the *Henry Draper Catalog* (1918–1924) and its extension (1925–1936). The catalog is considered to be a standard for stellar spectroscopy.

Cannon's 43-year career did not go unrewarded. In addition to receiving credit for the Draper catalogs, she also received recognition for discovering over 300 variable stars (which she incorporated into a catalog) and five novae. Cannon was the first woman to receive a doctor of astronomy degree from Groningen University (1921) and an honorary doctorate from Oxford University (1925). She was also the first woman to hold an office in the American Astronomical Society and to receive the Draper Award from the National Academy of Sciences (1931).

Scientists have used the work of Cannon and her successors to derive such information about stars as their motion, composition, brightness, and temperature. In turn, this information has led to theories about stellar life cycles. Modern astronomers, equipped with superior spectroscopes and computers have improved upon Cannon's work and are now able to sort stars into several hundred spectrographic categories. Evolving theories based upon such data are the legacy of Annie Jump Cannon's pioneering work in astronomy.

See also Stellar life cycle

CANYON

A canyon is a narrow, steep-walled, and deep valley with or without a perennial stream at the bottom. It is larger than, but otherwise similar to, a gorge. Canyon walls are commonly composed of **bedrock** with little or no **regolith** and those with nearly vertical walls, particularly in the southwestern United States, are often referred to as slot canyons.

Canyons are characteristic of high plateaus and mountainous regions that have experienced rapid tectonic uplift, for example the Colorado Plateau physiographic province of the southwestern United States. As a region is raised due to tectonic activity, streams will adjust themselves to the change by cutting deeper valleys. Rising or falling sea levels, particularly during glacial periods, can also affect stream incision rates and valley shapes although generally not to the same degree as tectonic activity.

Canyon formation is common in arid and semi-arid climates because bedrock weathers slowly in the absence of **water**. Therefore, canyon-forming streams are able to cut vertically much more rapidly than their valleys can be widened by **mass wasting** or other erosional processes. A canyon eroded into relatively uniform bedrock, for example the Grand Canyon of the Yellowstone River or the Black Canyon of the Gunnison River, will have a generally uniform valley wall profile with no abrupt changes in slope. Canyons eroded into layered rocks with differing degrees of resistance to **erosion**, however, will have irregular or stair-stepped valley wall profiles. This is the case in the Grand Canyon in Arizona, where hard **sandstone** and **limestone** layers, as well as the metamorphic rocks of the inner gorge, form steep cliffs whereas softer shale layers form gentle slopes or benches.

Rivers running through canyons are unable to develop broad **floodplains** because they are not free to migrate laterally and deposit alluvium. Stream terraces, where they do occur, are likely to be highly localized and discontinuous. Most of the sediment delivered to canyon bottoms arrives by mass wasting processes such as **rockfall** or by debris flows when rockfall debris along side channels is mobilized during rainstorms. Rockfall accumulations and alluvial fans formed when debris flows enter the main canyon can in turn restrict stream flow and create the alternating pools and **rapids** characteristic of many canyons.

See also Alluvial system; Bedrock; Channel patterns; Drainage basins and drainage patterns; Landscape evolution; Rapids and waterfalls; Rivers; Stream valleys, channels, and floodplains

CARBON

Carbon is the non-metallic chemical element of **atomic number** 6 in Group 14 of the **periodic table**, symbol C, atomic weight 12.01, specific **gravity** as **graphite** 2.25, as **diamond** 3.51. Its stable isotopes are ^{12}C (98.90%) and ^{13}C (1.10%). The weight of the ^{12}C **atom** is the international standard on which atomic weights are based. It is defined as weighing exactly 12.00000 **atomic mass** units.

Carbon has been known since prehistoric times. It gets its name from *carbo*, the Latin word for charcoal, which is almost pure carbon. In various forms, carbon is found not only on Earth, but in the atmospheres of other planets, in the **Sun** and stars, in **comets** and in some meteorites.

On Earth, carbon can be considered the most important of all the **chemical elements**, because it is the essential element in practically all of the chemical compounds in living things. Carbon compounds are what make the processes of life work. Beyond Earth, carbon-atom nuclei are an essential part of the **nuclear fusion** reactions that produce the energy of the Sun and of many other stars. Without carbon, the Sun would be cold and dark.

In the form of chemical compounds, carbon is distributed throughout the world as **carbon dioxide** gas, CO_2, in the atmosphere and dissolved in all the **rivers**, **lakes** and **oceans**. In the form of carbonates, mostly calcium carbonate ($CaCO_3$), it occurs as huge rocky masses of **limestone**, **marble** and chalk. In the form of **hydrocarbons**, it occurs as great deposits of **natural gas**, **petroleum** and **coal**. Coal is important not only as a fuel, but because it is the source of the carbon that is dissolved in molten **iron** to make steel.

All plants and animals on Earth contain a substantial proportion of carbon. After hydrogen and **oxygen**, carbon is the most abundant element in the human body, making up 10.7% of all the body's atoms.

Carbon is found as the free (uncombined) element in three different allotropic forms-different geometrical arrangements of the atoms in the solid. The two crystalline forms (forms containing very definite atomic arrangements) are graphite and diamond. Graphite is one of the softest known materials, while diamond is one of the hardest.

There is also a shapeless, or **amorphous**, form of carbon in which the atoms have no particular geometric arrangement. Carbon black, a form of amorphous carbon obtained from smoky flames, is used to make rubber tires and inks black. Charcoal—wood or other plant material that has been heated in the absence of enough air to actually burn—is mostly amorphous carbon, but it retains some of the microscopic structure of the plant cells in the wood from which it was made. Activated charcoal is charcoal that has been steam-purified of all the gummy wood-decomposition products, leaving porous grains of pure carbon that have an enormous microscopic surface **area**. It is estimated that one cubic inch of activated charcoal contains 200,000 ft^2 (18,580 m^2) of microscopic surface. This huge surface has a stickiness, called adsorption, for molecules of gases and solids; activated charcoal is therefore used to remove impurities from **water** and air, such as in home water purifiers and in gas masks.

Graphite is a soft, shiny, dark gray or black, greasy-feeling mineral that is found in large masses throughout the world, including the United States, Brazil, England, western **Europe**, Siberia, and Sri Lanka. It is a good conductor of **electricity** and resists temperatures up to about 6,332°F (3,500°C), which makes it useful as brushes (conductors that slide along rotating parts) in electric motors and generators, and as electrodes in high-temperature electrolysiscells. Because of its slipperiness, it is used as a lubricant. For example, powdered graphite is used to lubricate locks, where oil might be too viscous. The "lead" in pencils is actually a mixture of graphite, **clay,** and wax. It is called "lead" because the metallic element **lead** (Pb) leaves gray marks on paper and was used for writing in ancient times. When graphite-based pencils came into use, they were called "lead pencils."

The reason for graphite's slipperiness is its unusual crystalline structure. It consists of a stack of one-atom-thick sheets of carbon atoms, bonded tightly together into a hexagonal pattern in each sheet, but with only very weak attractions—much weaker than actual chemical bonds—holding the sheets together. The sheets of carbon atoms can therefore slide easily over one another; graphite is slippery in the same way as layers of wet leaves on a sidewalk.

Diamond, the other crystalline form of pure carbon, is the world's hardest natural material, and is used in industry as an abrasive and in drill tips for drilling through **rock** in oil fields and human teeth in dentists' offices. On a hardness scale of one to ten, which mineralogists refer to as the Mohs scale of hardness, diamond is awarded a perfect ten. But that's not why diamonds are so expensive. They are the most expensive of all gems, and are kept that way by supply and demand. The supply is largely controlled by the De Beers Consolidated Mines, Inc. in South **Africa**, where most of the world's diamonds are mined, and the demand is kept high by the importance that is widely attributed to diamonds.

A diamond can be considered to be a single huge molecule consisting of nothing but carbon atoms that are strongly bonded to each other by covalent bonds, just as in other molecules. A one-carat diamond "molecule" contains 10^{22} carbon atoms.

The beauty of gem-quality diamonds comes from their crystal clarity, their high refractivity (ability to bend light rays) and their high dispersion—their ability to spread light of different colors apart, which makes the diamond's **rainbow** "fire." Skillful chipping of the gems into facets (flat faces) at carefully calculated angles makes the most of their sparkle. Even though diamonds are hard, meaning that they can't be scratched by other materials, they are brittle—they can be cracked.

Carbon is unique among the elements because its atoms can form an endless variety of molecules with an endless variety of sizes, shapes and chemical properties. No other element can do that to anywhere near the degree that carbon can. In the **evolution** of life on Earth, nature has always been able to "find" just the right carbon compound out of the millions available, to serve just about any required function in the complicated **chemistry** of living things.

Carbon-containing compounds are called organic compounds, and the study of their properties and reactions is called organic chemistry. The name organic was originally given to those substances that are found in living organisms—plants and animals. Almost all of the chemical substances in living things are carbon compounds (water and **minerals** are the obvious exceptions), and the name organic was eventually applied to the chemistry of all carbon compounds, regardless of where they come from.

Having the atomic number six, every carbon atom has a total of six protons. Therefore, all carbon atoms with a neutral charge also have a total of six electrons. Two are in a completed inner orbit, while the other four are valence electrons-outer electrons that are available for forming bonds with other atoms. An ion is an atom with either a negative or positive charge has either less or more electrons than the number of protons (respectively), and is referred to as either an anion (negatively charged) or a cation (positively charged).

It is impossible to summarize the properties of carbon's millions of compounds. Organic compounds can be classified into families that have similar properties, because they have certain groupings of atoms in common.

See also Carbon dating; Chemical bonds and physical properties; Chemical elements; Gemstones; Geochemistry; Historical geology

CARBON DATING

Carbon dating is a technique used to determine the approximate age of once-living materials. It is based on the decay rate of the radioactive carbon isotope ^{14}C, a form of carbon taken in by all living organisms while they are alive.

Before the twentieth century, determining the age of ancient **fossils** or artifacts was considered the job of paleontologists or paleontologists, not nuclear physicists. By comparing the placement of objects with the age of the **rock** and silt layers in which they were found, scientists could usually make a general estimate of their age. However, many objects were found in caves, frozen in **ice**, or in other areas whose ages were not known; in these cases, it was clear that a method for dating the actual object was necessary.

In 1907, the American chemist Bertram Boltwood (1870–1927) proposed that rocks containing radioactive uranium could be dated by measuring the amount of **lead** in the sample. This was because uranium, as it underwent radioactive decay, would transmute into lead over a long span of time. Thus, the greater the amount of lead, the older the rock. Boltwood used this method, called radioactive dating, to obtain a very accurate measurement of the age of Earth. While the uranium-lead dating method was limited (being only applicable to samples containing uranium), it was proved to scientists that radioactive dating was both possible and reliable.

The first method for dating organic objects (such as the remains of plants and animals) was developed by another American chemist, Willard Libby (1908–1980). He became intrigued by carbon–14, a radioactive isotope of carbon. Carbon has isotopes with atomic weights between 9 and 15. The most abundant isotope in nature is carbon–12, followed in abundance by carbon–13. Together carbon–12 and carbon–13 make up 99% of all naturally occurring carbon. Among the less abundant isotopes is carbon–14, which is produced in small quantities in the earth's atmosphere through interactions involving cosmic rays. In any living organism, the relative concentration of carbon–14 is the same as it is in the atmosphere because of the interchange of this isotope between the organism and the air. This carbon–14 cycles through an organism while it is alive, but once it dies, the organism accumulates no additional carbon–14. Whatever carbon–14 was present at the time of the organism's death begins to decay to nitrogen–14 by emitting radiation in a process known as beta decay. The difference between the concentration of carbon–14 in the material to be dated and the concentration in the atmosphere provides a basis for estimating the age of a specimen, given that the rate of decay of carbon–14 is well known. The length of time required for one-half of the unstable carbon–14 nuclei to decay (i.e., the **half-life**) is 5,730 years.

Libby began testing his carbon–14 dating procedure by dating objects whose ages were already known, such as samples from Egyptian tombs. He found that his methods, while not as accurate as he had hoped, were fairly reliable. He continued his research and, through improvements in his equipment and procedures, was eventually able to determine the age of an object up to 50,000 years old with a precision of plus-or-minus 10%. Libby's method, called radiocarbon or carbon–14 dating, gave new impetus to the science of radioactive dating. Using the carbon–14 method, scientists determined the ages of artifacts from many ancient civilizations. Still, even with the help of laboratories worldwide, radiocarbon dating was only accurate up to 70,000 years old, since objects older than this contained far too little carbon–14 for the equipment to detect.

Starting where Boltwood and Libby left off, scientists began to search for other long-lived isotopes. They developed the uranium-thorium method, the potassium-argon method, and the rubidium-strontium method, all of which are based on the transformation of one element into another. They also improved the equipment used to detect these elements, and in 1939, scientists first used a cyclotron particle accelerator as a mass spectrometer. Using the cyclotron, carbon–14 dating could be used for objects as old as 100,000 years, while samples containing radioactive beryllium could be dated as far back as 10–30 million years. A newer method of radioactive tracing involves the use of a new clock, based on the radioactive decay of ^{235}uranium to ^{231}protactinium.

See also Fossils and fossilization; Geochemistry

CARBON DIOXIDE

Carbon dioxide was the first gas to be distinguished from ordinary air, perhaps because it is so intimately connected with the cycles of plant and animal life. Carbon dioxide is released during respiration and combustion. When plants store energy in the form of food, they use up carbon dioxide. Early scientists were able to observe the effects of carbon dioxide long before they knew its function.

About 1630, Flemish scientist Jan van Helmont discovered that certain vapors differed from air that was then thought to be a single substance or element. Van Helmont coined the term gas to describe these vapors and collected the gas given off by burning wood, calling it gas sylvestre. Today, it is known that this gas is carbon dioxide, and van Helmont is credited with its discovery. In 1756, Joseph Black proved that carbon dioxide, which he called fixed air, is present in the atmosphere and that it combines with other chemicals to form new compounds. Black also identified carbon dioxide in exhaled breath, determined that the gas is heavier than air, and characterized its chemical behavior as that of a weak acid. The pioneering work of van Helmont and Black soon led to the discovery of other gases. As a result, scientists began to realize that gases must be weighed and accounted for in the analysis of chemical compounds, just like solids and liquids.

In 1783, French physicist Pierre Laplace (1749–1827) used a guinea pig to demonstrate quantitatively that **oxygen** from the air is used to burn carbon stored in the body and produce carbon dioxide in exhaled breath. Around the same time, chemists began drawing the connection between carbon dioxide and plant life. Like animals, plants breathe using up oxygen and releasing carbon dioxide. Plants, however, also have the unique ability to store energy in the form of carbohydrates, our primary source of food. This energy-storing process, called photosynthesis, is essentially the reverse of respiration. It uses up carbon dioxide and releases oxygen in a complex series of reactions that also require sunlight and chlorophyll (the green substance that gives plants their color). In the 1770s, Dutch physiologist Jan Ingen Housz established the principles of photosynthesis.

English chemist John Dalton guessed in 1803 that the molecule contains one carbon **atom** and two oxygen atoms (CO_2); this was later proved correct. The decay of all organic materials produces carbon dioxide slowly, and Earth's atmosphere contains a small amount of the gas (about 0.033%). Spectroscopic analysis has shown that in our **solar system**, the planets of Venus and Mars have atmospheres rich in carbon dioxide. The gas also exists in ocean **water**, where it plays a vital role in marine plant photosynthesis.

In modern life, carbon dioxide has many practical applications. For example, fire extinguishers use CO_2 to control electrical and oil fires that cannot be put out with water. Because carbon dioxide is heavier than air, it spreads into a blanket and smothers the flames. Carbon dioxide is also an effective refrigerant. In its solid form, known as dry **ice**, it is used to chill perishable food during transport. Many industrial processes are also cooled by carbon dioxide, which allows faster production rates. For these commercial purposes, carbon dioxide can be obtained from either **natural gas** wells, fermentation of organic material, or combustion of fossil **fuels**.

Recently, carbon dioxide has received negative attention as a greenhouse gas. When it accumulates in the upper atmosphere, it traps the Earth's heat, eventually causing **global warming**. Since the beginning of the industrial revolution in the mid 1800s, factories and power plants have significantly increased the amount of carbon dioxide in the atmosphere by burning **coal** and other fossil fuels. This effect was first predicted by **Svante August Arrhenius**, a Swedish physicist, in the 1880s. Then in 1938, British physicist G. S. Callendar suggested that higher CO_2levels had caused the warmer temperatures observed in America and **Europe** since Arrhenius's day. Modern scientists have confirmed these views and identified other causes of increasing carbon dioxide levels, such as the clearing of the world's **forests**. Because trees extract CO_2 from the air, their depletion has contributed to upsetting the delicate balance of gases in the atmosphere.

In rare circumstances, carbon dioxide can endanger life. In 1986, a huge cloud of the gas exploded from Lake Nyos, a volcanic lake in northwestern Cameroon, and quickly suffocated more than 1,700 people and 8,000 animals. Scientists have attempted to control this phenomenon by slowly pumping the gas up from the bottom of the lake.

See also Atmospheric chemistry; Atmospheric composition and structure; Atmospheric pollution; Forests and deforestation; Global warming; Greenhouse gases and greenhouse effect

CARBON MONOXIDE • *see* ATMOSPHERIC POLLUTION

CARBONIFEROUS PERIOD • *see* MISSISSIPPIAN PERIOD

CARMICHAEL STOPES, MARIE CHARLOTTE (1880-1958)

Scottish geologist, paleobotanist, and social reformer

Although best known for her later work on birth control issues, Marie Stopes began her career as a geologist and paleobotantist. Stopes advanced the classification of coal-associated macerals (microscopic organic portions of **coal**) through an identification system. Stopes' work on petrography (the classification of coal and other **petroleum** related deposits) contributed to the modern system of identification based upon color, reflecting ability, and general morphology. Stopes' was an accomplished expert on the subject of coal balls (roundish nodules composed of mineral and plant deposits).

Stopes was born in Edinburgh, Scotland to the English architect, archeologist, and geologist Henry Stopes (1852–1902) and his feminist wife, Charlotte Carmichael (1841–1929), one of the first women to attend a Scottish university. Stopes and her younger sister, Winnie, were raised in London in a curious mixture of socially progressive scientific thought and stern Scottish Protestantism. Her authoritarian mother trusted the Bible, but supported woman suffrage, clothing reform, and free thought. Stopes' father cared mainly for science. As a young girl Stopes met many of her father's friends in the British Association for the Advancement of Science, including Francis Galton (1822–1911), Thomas Henry Huxley (1825–1895), Norman McColl (1843–1904), and Charles Edward Sayle (1864–1924). Through them came Stopes' interest in Charles Darwin, **evolution**, and eventually, eugenics.

Stopes enrolled at University College, London, in 1900 on a science scholarship, graduating with a B.Sc. in 1902 with honors in botany and **geology**. She did graduate work there until 1903, then at the University of Munich, where she received her Ph.D. in paleobotany in June 1904. In October of the same year, Stopes became the first woman scientist on the faculty of the University of Manchester. In 1905, University College made her the youngest Briton of either gender to earn the D.Sc. She studied at the Imperial University of Tokyo from 1907 to 1908, then returned to Manchester in 1909. Stopes married botanist and geneticist Reginald Ruggles Gates (1882–1962) in 1911, but obtained an annulment five years later.

Inspired by meeting Margaret Sanger (1879–1966) in 1915, Marie Stopes began crusading for sexual freedom and birth control. With her second husband, Humphrey Verdon Roe (1878–1949), she opened the first birth control clinic in Great Britain, “The Mothers' Clinic” in Holloway, North London, on 17 March 1921.

Devoted to eugenics, Stopes founded the Society for Constructive Birth Control and Racial Progress in 1921, and after 1937 was a Life Fellow of the British Eugenics Society. Stopes become controversial, in part because she advocated the involuntary sterilization of anyone she deemed unfit for parenthood, including the mentally impaired, addicts, subversives, criminals, and those of mixed racial origin. At one time, Stopes persecuted her son, Harry Stopes Roe (b. 1924), for marrying a woman with bad eyesight. While Sanger's main motivation in promoting birth control was to relieve the misery of the poor, Stopes campaigned vigorously and often flamboyantly for birth control to prevent ‘‘inferior” women from reproducing, and to allow all women to lead sexually fulfilling lives without fear of pregnancy. Stopes made enemies on all sides of the issue. Havelock Ellis Sanger (1859–1939), and other left-leaning rivals within the birth control movement accused her of anti-Semitism, political conservatism, and egomania. Stopes' strongest opposition came from the Roman Catholic Church, especially because, unlike most other early advocates of birth control, she did not oppose abortion.

By her own account Stopes had three distinct careers, a scientist until about 1914, a social reformer until the late 1930s, and a poet thereafter. Among her books are *Married Love: A New Contribution to the Solution of Sex Difficulties* (1918), *Wise Parenthood: A Sequel to “Married Love”: A Book for Married People* (1919), *Radiant Motherhood: A Book for Those who are Creating the Future* (1920), *Contraception (Birth Control): Its Theory, History and Practice* (1923), *The Human Body* (1926), *Sex and the Young* (1926), *Enduring Passion: Further New Contributions to the*

Solution of Sex Difficulties (1928), *Mother England: A Contemporary History* (1929), *Roman Catholic Methods of Birth Control* (1933), *Birth Control To-Day* (1934), *Marriage in my Time* (1935), *Change of Life in Men and Women* (1936), and *Your Baby's First Year* (1939). Stopes died quietly at her home near Dorking, Surrey, England.

See also Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration

CARSON, RACHEL (1907-1964)

American marine biologist

Rachel Carson is best known for her 1962 book, *Silent Spring,* which is often credited with beginning the modern environmental movement in the United States. The book focused on the uncontrolled and often indiscriminate use of pesticides, especially dichlorodiphenyltrichloroethane (commonly known as DDT), and the irreparable environmental damage caused by these chemicals. The public outcry Carson generated by the book motivated the United States Senate to form a committee to investigate pesticide use. Her eloquent testimony before the committee altered the views of many government officials and helped lead to the creation of the Environmental Protection Agency (EPA).

Rachel Louise Carson, the youngest of three children, was born in Springdale, Pennsylvania, a small town twenty miles north of Pittsburgh. Her parents, Robert Warden and Maria McLean Carson, lived on 65 acres and kept cows, chickens, and horses. Although the land was not a true working farm, it had plenty of woods, animals, and streams, and here, near the shores of the Allegheny River, Carson learned about the relationship between the land and animals.

Carson's mother instilled in Rachel a love of nature, and taught her the intricacies of music, art, and literature. Carson's early life was one of isolation; she had few friends besides her cats, and she spent most of her time reading and pursuing the study of nature. She began writing poetry at age eight and published her first story, "A Battle in the Clouds," in *St. Nicholas* magazine at the age of 10. She later claimed that her professional writing career began at age 11, when *St. Nicholas* paid her a little over three dollars for one of her essays.

Carson planned to pursue a career as a writer when she received a scholarship in 1925 from the Pennsylvania College for Women (now Chatham College) in Pittsburgh. At the college she fell under the influence of Mary Scott Skinker, whose freshman biology course altered her career plans. In the middle of her junior year, Carson switched her major from English to zoology, and in 1928, she graduated magnum cum laude. "Biology has given me something to write about," she wrote to a friend, as quoted in *Carnegie* magazine. "I will try in my writing to make animals in the woods or waters, where they live, as alive to others as they are to me."

With Skinker's help, Carson obtained first a summer fellowship at the Marine Biology Laboratory at Woods Hole in Massachusetts and then a one-year scholarship from the Johns Hopkins University in Baltimore. While at Woods Hole over the summer, she saw the ocean for the first time and encountered her first exotic sea creatures, including sea anemones and sea urchins. At Johns Hopkins, she studied zoology and genetics. Graduate school did not proceed smoothly; she encountered financial problems and experimental difficulties but eventually managed to finish her highly detailed master's dissertation, "The Development of the Pronephoros during the Embryonic and Early Larval Life of the Catfish (*Inctalurus punctaltus*)." In June 1932, she received her master's degree.

Before beginning her graduate studies at Johns Hopkins, Carson had arranged an interview with Elmer Higgins, who was head of the Division of Scientific Inquiry at the U.S. Bureau of Fisheries. Carson wanted to discuss her job prospects in marine biology, and Higgins had been encouraging, though he then had little to offer. Carson contacted Higgins again at this time, and she discovered that he had an opening at the Bureau of Fisheries for a part-time science writer to work on radio scripts. The only obstacle was the civil service exam, which women were then discouraged from taking. Carson not only did well on the test, she outscored all other applicants. She went on to become only the second woman ever hired by the bureau for a permanent professional post.

At the Bureau of Fisheries, Carson wrote and edited a variety of government publications—everything from pamphlets on how to cook fish to professional scientific journals. She earned a reputation as a ruthless editor who would not tolerate inconsistencies, weak prose, or ambiguity. One of her early radio scripts was rejected by Higgins because he found it too "literary." He suggested that she submit the script in essay form to the *Atlantic Monthly,* then one of the nation's premier literary magazines. To Carson's amazement, the article was accepted and published as "Undersea" in 1937. Her jubilation over the article was tempered by personal family tragedy. Her older sister, Marian, died at age forty that same year, and Carson had to assume responsibility for Marian's children, Marjorie and Virginia Williams.

The *Atlantic Monthly* article attracted the notice of an editor at the publishing house of Simon & Schuster, who urged Carson to expand the four-page essay into book form. Working diligently in the evenings, she was able to complete the book in a few years; it was published as *Under the Sea-Wind*. Unfortunately, the book appeared in print in 1941, just one month before the Japanese attacked Pearl Harbor. Despite favorable, even laudatory reviews, it sold fewer than 1,600 copies after six years in print. It did, however, bring Carson to the attention of a number of key people, including the influential science writer William Beebe. Beebe published an excerpt from *Under the Sea-Wind* in his 1944 compilation *The Book of Naturalists*, including Carson's work alongside the writings of Aristotle, Audubon, and Thoreau.

The poor sales of *Under the Sea-Wind* compelled Carson to concentrate on her government job. The Bureau of Fisheries merged with the Biological Survey in 1940, and was reborn as the Fish and Wildlife Service. Carson quickly moved up the professional ranks, eventually reaching the position of biologist and chief editor after World War II. One of her postwar assignments, a booklet about National Wildlife Refuges called *Conservation in Action*, took her back into the field. As part of her research, she visited the Florida Everglades, Parker River in Massachusetts, and Chincoteague Island in the Chesapeake Bay.

After the war, Carson began work on a new book that focused on **oceanography**. She was now at liberty to use previously classified government research data on oceanography, which included a number of technical and scientific breakthroughs. As part of her research, she did some undersea diving off the Florida coast during the summer of 1949. She battled skeptical administrators to arrange a deep-sea cruise to Georges Bank near Nova Scotia aboard the Fish and Wildlife Service's research vessel, the *Albatross III*.

Entitled *The Sea around Us*, her book on oceanography was published on July 2, 1951. It was an unexpected success, and remained on the *New York Times* bestseller list for 86 weeks. The book brought Carson numerous awards, including the National Book Award and the John Burroughs Medal, as well as honorary doctorates from her alma mater and Oberlin College. Despite her inherent shyness, Carson became a regular on the lecture circuit. With financial security no longer the overriding concern it had been, she retired from government service and devoted her time to writing.

Carson began work on another book, focusing this time on the intricacies of life along the shoreline. She took excursions to the mangrove coasts of Florida and returned to one of her favorite locations, the rocky shores of Maine. She fell in love with the Maine coast and in 1953 bought a summer home in West Southport on the shore of Sheepscot Bay. *The Edge of the Sea* was published in 1955 and earned Carson two more prestigious awards, the Achievement Award of the American Association of University Women and a citation from the National Council of Women of the United States. The book remained on the bestseller list for 20 weeks, and RKO Studios bought the rights to it. In Hollywood, the studio sensationalized the material and ignored scientific fact. Carson corrected some of the more egregious errors but still found the film embarrassing, even after it won an Oscar as the best full-length documentary of 1953.

From 1955 to 1957, Carson concentrated on smaller projects, including a telescript, "Something about the Sky," for the *Omnibus* series. She also contributed a number of articles to popular magazines. In July 1956, Carson published "Help Your Child to Wonder" in the *Woman's Home Companion*. The article was based on her own real-life experiences, something rare for Carson. She intended to expand the article into a book and retell the story of her early life on her parent's Pennsylvania farm. After her death, the essay reappeared in 1965 as the book *The Sense of Wonder*.

In 1956, one of the nieces Carson had raised died at age 36. Marjorie left her son Roger; Carson now cared for him in addition to her mother. She legally adopted Roger that same year and began looking for a suitable place to rear the child. She built a new winter home in Silver Spring, Maryland, on an uncultivated tract of land, and she began another project shortly after the home was finished. The luxuriant setting inspired her to turn her thoughts to nature once again. Carson's next book grew out of a long-held concern about the overuse of pesticides. She had received a letter from Olga Owens Huckins, who related how the aerial spraying of DDT had destroyed her Massachusetts bird sanctuary. Huckins asked her to petition federal authorities to investigate the widespread use of such pesticides, but Carson thought the most effective tactic would be to write an article for a popular magazine. When her initial queries were rejected, Carson attempted to interest the well-known essayist E. B. White in the subject. White suggested she write the article herself, in her own style, and he told her to contact William Shawn, an editor at the *New Yorker*. Eventually, after numerous discussions with Shawn and others, she decided to write a book instead.

The international reputation Carson now enjoyed enabled her to enlist the aid of an array of experts. She consulted with biologists, chemists, entomologists, and pathologists, spending four years gathering data for her book. When *Silent Spring* first appeared in serial form in the *New Yorker* in June 1962, it drew an aggressive response from the chemical industry. Carson argued that the environmental consequences of pesticide use underscored the futility of humanity's attempts to control nature, and she maintained that these efforts to assume control had upset nature's delicate balance. Although the message is now largely accepted, the book caused controversy in some circles, challenging the long-held belief that humans could master nature. The chemical companies, in particular, attacked both the book and its author; they questioned the data, the interpretation of the data, and the author's scientific credentials. One early reviewer referred to Carson as a "hysterical woman," and others continued this sexist line of attack. Some chemical companies attempted to pressure Houghton Mifflin, the book's publisher, into suppressing the book, but these attempts failed.

The general reviews were much kinder and *Silent Spring* soon attracted a large, concerned audience, both in America and abroad. A special CBS television broadcast, "The Silent Spring of Rachel Carson," which aired on April 3, 1963, pitted Carson against a chemical company spokesman. Her cool-headed, commonsense approach won her many followers and brought national attention to the problem of pesticide use. The book became a cultural icon and part of everyday household conversation. Carson received hundreds of invitations to speak, most of which she declined due to her deteriorating health. She did find the strength to appear before the Women's National Press Club, the National Parks Association, and the Ribicoff Committee—the U.S. Senate committee on environmental hazards.

In 1963, Carson received numerous honors and awards, including an award from the Izaak Walton League of America, the Audubon Medal, and the Cullen Medal of the American Geographical Society. That same year, she was elected to the prestigious American Academy of Arts and Sciences. Carson died of heart failure at the age of 56. In 1980, President Jimmy Carter posthumously awarded her the President's Medal of Freedom. A Rachel Carson stamp was issued by the U.S. Postal Service in 1981.

See also Environmental pollution

CARTOGRAPHY

Cartography is the creation, production, and study of maps. It is considered a subdiscipline of geography, the study of spatial distribution of various phenomena. Cartographers are often geographers who particularly enjoy the combination of art, science, and technology employed in the making and studying of maps.

A map is a generalized two-dimensional representation of the spatial distribution of one or more phenomena. For example, a map may show the location of cities, mountain ranges, and **rivers**, or may show the types of **rock** in a given region. Maps are flat, making their production, storage, and handling relatively easy. Maps present their information to the viewer at a reduced scale. They are smaller than the **area** they represent, using mathematical relationships to maintain proportionally accurate geographic relationships between various phenomena. Maps show the location of selected phenomena by using symbols that are identified in a legend.

There are many different types of maps. A common classification system divides maps into two categories, general and thematic. General maps are maps that show spatial relationships between a variety of geographic features and phenomena, emphasizing their location relative to one another. Thematic maps illustrate the spatial variations of a single phenomenon, or the spatial relationship between two particular phenomena, emphasizing the pattern of the distribution.

Many maps can be either general or thematic, depending on the intent of the cartographer. For example, a cartographer may produce a vegetation map, one that shows the distribution of various plant communities. If the cartographer shows the location of various plant communities in relation to a number of other geographic features, the map is properly considered a general map. The map is more likely to be considered thematic if the cartographer uses it to focus on something about the relationship of the plant communities to each other, or to another particular phenomenon or feature, such as the differences in plant communities associated with changes in elevation or changes in **soil** type.

Some examples of general maps include large-scale and medium-scale topographic maps, planometric maps, and charts. Topographic maps show all-important physical and cultural features, including **relief**. Relief is the difference in elevation of various parts of the earth's surface. Planometric maps are similar to topographic maps, but omit changes in elevation. Charts are used by the navigators of aircraft and seagoing vessels to establish bearings and plot positions and courses. World maps on a small- or medium-scale showing physical and cultural features, such as those in atlases, are also considered general maps.

Although the subject matter of thematic maps is nearly infinite, cartographers use common techniques involving points, lines, and aerial photos to illustrate the structure of spatial distribution. Isarithmic maps use lines to connect points of equal value; these lines are called isopleths, or isolines. Isopleths used for a particular phenomenon may have a particular name; for example, isotherms connect points of equal **temperature**, **isobars** connect points of equal air pressure, and isohyets connect points of equal **precipitation**. Isopleths indicating differences in elevation are called contour lines. Isopleths are used to show how certain quantities change with location.


Cartographer at work. © *Christopher Cormack/Corbis. Reproduced by permission.*

A topographic map is a good example of how isopleths are used to present information. Topographic maps use isopleths called contour lines to indicate variations in relief. Each contour line connects points of the same elevation. Adjacent lines indicate variations in relief; these variations are called contour intervals. The contour interval is indicated in the map legend. A contour interval of 20 ft (6.1 m) means that there is a 20 ft (6.1 m) difference in elevation between the points connected by one contour line and the points connected by the adjacent contour line. The closer the lines are to each other, the more dramatic the change in elevation.

Chloropleth maps are another type of thematic map. They use areas of graduated gray tones or a series of gradually intensifying colors to show spatial variations in the magnitude of a phenomenon. Greater magnitudes are symbolized by either darker gray tones or more intense colors; lesser magnitudes are indicated by lighter gray tones or less intense colors.

Cartographers traditionally obtained their information from navigators and surveyors. Explorations that expanded the geographical awareness of a map-making culture also resulted in increasingly sophisticated and accurate maps. Today, cartographers incorporate information from aerial photography and **satellite** imagery in the maps they create.

Modern cartographers face three major design challenges when creating a map. First, they must decide how to accurately portray that portion of Earth's surface that the map will represent; that is, they must figure out how to represent three-dimensional objects in two dimensions. Second, cartographers must represent geographic relationships at a reduced size while maintaining their proportional relationships. Third, they must select which pieces of information will be included in the map, and develop a system of generalization, which will make the information presented by the map useful and accessible to its readers.

When creating a flat map of a portion of the earth's surface, cartographers first locate their specific area of interest using **latitude and longitude**. They then use map **projection** techniques to represent the three-dimensional characteristics of that area in two dimensions. Finally, a grid, called a rectangular coordinate system, may be superimposed on the map, making it easier to use.

Distance and direction are used to describe the position of something in **space**, its location. In conversation, terms like right and left, up and down, or here and there are used to indicate direction and distance. These terms are useful only if the location of the speaker is known; in other words, they are relative. Cartographers, however, need objective terms for describing location The system of latitude and longitude, a geographical coordinate system developed by the Greeks, is used by cartographers for describing location.

Earth is a sphere, rotating around an axis tilted approximately 23.5 degrees off the perpendicular. The two points where the axis intersects the earth's surface are called the poles. The equator is an imaginary circle drawn around the center of the earth, equidistant from both poles. A plane that sliced through the earth at the equator would intersect the axis of the earth at a right angle. Lines drawn around the earth to the north and south of the equator and at right angles to the earth's axis are called parallels. Any point on the earth's surface is located on a parallel.

An arc is established when an angle is drawn from the equator to the axis and then north or south to a parallel. Latitude is the measurement of this arc in degrees. There are 90 degrees from the equator to each pole, and sixty minutes in each degree. Latitude is used to determine distance and direction north and south of the equator.

Meridians are lines running from the north pole to the south pole, dividing the earth's surface into sections, like those of an orange. Meridians intersect parallels at right angles, creating a grid. Just as the equator acts as the line from which to measure north or south, a particular meridian, called the prime meridian, acts as the line from which to measure east or west. There is no meridian that has a natural basis for being considered the prime meridian. The prime meridian is established by international agreement; currently, it runs through the Royal Observatory in Greenwich, England. Longitude is the measurement in degrees of the arc created by an angle drawn from the prime meridian to the earth's axis and then east or west to a meridian. There are 180° west of the prime meridian and 180° east of it. The international date line lies approximately where the 180th meridian passes through the Pacific Ocean.

Using the geographical coordinate system of latitude and longitude, any point on the earth's surface can be located with precision. For example, Buenos Aires, the capital of Argentina, is located 34° 35 minutes south of the equator and 58° 22 minutes west of the prime meridian; Anchorage, the largest city of the state of Alaska, is located 61° 10 minutes north of the equator and 149°s 45 minutes west of the prime meridian.

After locating their area of interest using latitude and longitude, cartographers must determine how best to represent that particular portion of the earth's surface in two dimensions. They must do this in such a way that minimal amounts of distortion affect the geographic information the map is designed to convey.

Cartographers have developed map projections as a means for translating geographic information from a spherical surface onto a planar surface. A map projection is a method for representing a curved surface, such as the surface of the earth, on a flat surface, such as a piece of paper, so that each point on the curved surface corresponds to only one point on the flat surface.

There are many types of map projections. Some of them are based on geometry, others are based on mathematical formulas. None of them, however, can accurately represent all aspects of the earth's surface; inevitably there will be some distortion in shape, distance, direction or area. Each type of map projection is intended to reduce the distortion of a particular spatial element. Some projections reduce directional distortion, others try to present shapes or areas in as distortion-free a manner as possible. The cartographer must decide which of the many projections available will provide the most distortion-free presentation of the information to be mapped.

Maps present various pieces of geographical information at a reduced scale. In order for the information to be useful to the map reader, the relative proportions of geographic features and spatial relationships must be kept as accurate as possible. Cartographers use various types of scales to keep those features and relationships in the correct proportions.

No single map can accurately show every feature on the earth's surface. There is simply too much spatial information at any particular point on the earth's surface for all of the information to be presented in a comprehensible, usable format. In addition, the process of reduction has certain visual effects on geographic features and spatial relationships. Because every feature is reduced by the ratio of the reduction, the distance between features is reduced, crowding them closer together and lessening the clarity of the image. The width and length of individual features are also reduced.

See also Earth (planet); Topography and topographic maps; Weather forecasting methods

CATASTROPHIC MASS MOVEMENTS

Catastrophic mass movements are large and rapid **mass wasting** events such as landslides, rockslides, and **rock** avalanches. Although they are often believed to occur with no warning, catastrophic mass movements are often preceded by subtle changes such as rock **creep** that foreshadow their occurrence. Because of their speed and size, catastrophic mass movements are often fatal events.

One of the most notable catastrophic mass movements to have occurred during recorded times was associated with the May 18, 1980 eruption of Mount St. Helens. **Magma** movement produced a bulge on the north side of the **volcano** that failed as a series of three large landslides during a magnitude 5.2 **earthquake** on May 18, and was immediately followed by the well-known eruption. The volume of the material removed by the landslides is estimated to have been about 2.3 km^3. The landslides broke apart as they began to move and traveled downhill as a rock **avalanche**, which is a common form of catastrophic **mass movement**.

Other rock avalanches buried the towns of Frank, Alberta in 1903 and Elm, Switzerland in 1881; both of these events were triggered by miners undercutting steep slopes above the towns. In 1963 a large rockslide that traveled into the Vaiont reservoir in Italy produced a wave that overtopped the dam and killed many downstream residents. The Vaiont **landslide** was triggered by changes in the reservoir level as it was filled and emptied each year after its completion in 1960, which affected the **groundwater** pressure within the adjacent slopes. Earthquakes can also trigger catastrophic landslides without human intervention, but catastrophic landslides rarely appear to be triggered by rainfall. A notable example of an earthquake-triggered catastrophic landslide during recent times occurred in 1959, when a magnitude 7.5 earthquake triggered a landslide that dammed the Madison River in Montana, killing 26 people and creating Earthquake Lake. The geologic record contains evidence of even more catastrophic events, including prehistoric rock avalanches that involved as much as 20 km^3 of rock and traveled tens of kilometers from their points of origin.

One of the most perplexing aspects of catastrophic rock avalanches is that in many cases they begin as normal landslides but travel much longer distances than would be predicted by solving the simple **physics** problem of rock sliding along rock. The coefficients of friction necessary for rock avalanches larger than 10^6 m^3 to have traveled their observed distances decrease significantly as a function of the avalanche volume. A typical coefficient of friction for one piece of rock sliding past another might be about 0.55, and this is a value calculated for many small rockslides; in large rock avalanches, however, the coefficient of friction necessary to explain the travel distance can be as low as 0.05–0.10. In essence, rock avalanches move as though they are fluids rather than solid masses of rock and often run up the opposing sides of valleys before coming to rest. One early explanation of this phenomenon, based upon studies of the prehistoric Blackhawk landslide in California, was that rock avalanches glide atop pockets of air trapped beneath the rock mass. Other proposed friction reducing mechanisms have included the frictional heating of **water** to generate steam that would fluidize the avalanche and the **melting** of rock to produce a layer of liquid **glass** along the base of the avalanche. The discovery of rock avalanche deposits on Mars and the **Moon**, however, cast doubt on mechanisms such as air entrapment and steam generation because neither air nor water would have been available. A process known as acoustic fluidization has been proposed to explain the behavior of rock avalanches without requiring air pockets or steam generation. Acoustic fluidization occurs when elastic waves travel through a rock avalanche as it moves downhill, breaks into pieces, and is jostled by the underlying **topography**.

Mudslides can hit quickly with devastating results, as seen here. ***Jim Sugar. Jim Sugar Photgraphy/Corbis-Bettmann. Reproduced by permission.***

Because catastrophic rock avalanches are so rare and short lived, and because their remnants contain little evidence of the dynamic processes that occurred during movement, it is likely that explanations of their unusual mechanical behavior will always be inferences based largely on theoretical possibilities rather than empirical observations.

See also Catastrophism; Debris flow; Lahar

In 1908 over Tunguska, Russia, an object that is believed to have been either a comet or a stony meteorite exploded with the force of a nuclear bomb. If it had happened over an urban area instead of over Siberian wilderness, the loss of life would have been immense. *AP/Wide World. Reproduced by permission.*

CATASTROPHISM

Catastrophism is the argument that Earth's features—including mountains, valleys, and lakes—primarily formed and shaped as a result of the periodic but sudden forces as opposed to gradual change that takes place over a long period of time.

Although geologists may argue about the extent of catastrophism in shaping the earth, modern geologists interpret many formations and events as resulting from an interplay catastrophic and uniform forces that result in more slowly evolving change.

For example, according to strict catastrophe theory, one might interpret the origins of the Rocky Mountains or the Alps, as resulting from a huge **earthquake** that uplifted them quickly. When viewing the Yosemite Valley in California a catastrophist might not assert they were carved by **glaciers**, but rather the floor of the valley collapsed over 1,000 ft (305 m) to its present position in one giant plunge. Strict catastrophic theory also argues for long periods of inactivity following catastrophic events.

In terms of modern geoscience, strict catastrophic theory (e.g., a world shaped by large single **floods**, or massive earthquakes) finds little evidence or support. Catastrophism developed in the seventeenth and eighteenth centuries when, by tradition and even by law, scientists used the Bible and other religious documents as a scientific documents.

For example, when a prominent theologian, Irish biblical scholar Bishop James Ussher in the mid-1600's work, *Annals of the World*, counted the ages of people in the Bible and proclaimed that Earth was created in 4004 B.C. (In fact, Ussher even pronounced an actual date of creation as the evening of October 22), geologists tried to work within a time frame that encompassed only around six thousand years. (Current research estimates Earth at 4.5 billion years old.) In its original form, catastrophism eventually fell from grace with the scientific community as they reasoned more logical explanations for natural history. A new concept, known as **uniformitarianism**, eventually replaced catastrophism. Uniformitarianism is the argument that mountains are uplifted, valleys carved, and sediments deposited over immense time periods by the same physical forces and chemical reactions in evidence today.

Modern catastrophism—increasingly popular since the late 1970s—argues evidence that catastrophic forces can have a profound influence on shaping Earth. For example, modern catastrophic theory argues that large objects from **space** (**Asteroids**, **Comets**, etc.) periodically collide with Earth and that these collisions can have profound effects on both the **geology** and biology of Earth. Based on the extrapolation of experimental data and the observation of large-scale events (e.g., major **volcanic eruptions**), scientists speculate that when these objects strike, they clog the atmosphere with sunlight-blocking dust and gases, ignite forest fires, and trigger volcanism. One hypothesis advances that a large asteroid impact lead to the extinction of dinosaurs roughly 65 million years ago.

See also Cambrian Period; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Impact crater; K-T event; Origin of life; Orogeny; Plate tectonics; Precambrian; Torino scale

CATION • *see* CHEMICAL BONDS AND PHYSICAL PROPERTIES

CAVE

A cave is a naturally occurring hollow **area** inside the earth. Most caves are formed by some type of erosional process. The most notable exception is hollow **lava** tubes such as those found in the Hawaiian Islands. The formation of caves depends upon geologic, topographic, and hydrologic factors. These factors determine where and how caves develop, as well as their structure and shape. The study of caves is called speleology. Some caves may be small hillside openings, while others consist of large chambers and interconnecting tunnels and mazes. Openings to the surface may be large gaping holes or small crevices.

Caves hosted in rocks other than **limestone** are usually formed by **water** erosional processes. For example, **rivers** running through canyons with steep walls erode the **rock** at points where the current is strong. Such caves usually have large openings and are not too deep. Caves of this type can be found in the southwestern United States and were at one time inhabited by prehistoric American Indians known as Cliff Dwellers. Sea caves are formed by waves continually crashing against cliffs or steep walls. Often these caves can only be entered at low tide. **Ice** caves are also formed in **glaciers** and **icebergs** by meltwater that drains down crevices in the ice.

Lava caves, which are often several miles long, form when the exterior of a lava flow hardens and cools to form a roof, but lava below the surface flows out, leaving a hollow tube. **Wind** or aeolian caves usually form in **sandstone** cliffs as wind-blown **sand** abrades the cliff face. They are found in **desert** areas, and occur in a bottleneck shape with the entrance much smaller than the chamber. Talus caves are formed by boulders that have piled up on mountain slopes. The most common, largest, and spectacular caves are solution caves.

Solution caves form by chemical **weathering** of the surrounding **bedrock** as **groundwater** moves along fractures in the rock. These caves produce a particular type of terrain called karst. Karst terrain primarily forms in bedrock of calcium carbonate, or limestone, but can develop in any soluble sedimentary rock such as **dolomite**, rock **gypsum**, or rock salt. The host rock extends from near the earth's surface to below the **water table**. Several distinctive karst features make this terrain easy to identify. The most common are **sinkholes**, circular depressions where the underlying rock has been dissolved away. Disappearing streams and natural bridges are also common clues. Entrances to solution caves are not always obvious, and their discovery is sometimes quite by accident.

Formation of karst involves the chemical interaction of air, **soil**, water, and rock. As water flows over and drains into the earth's surface, it mixes with **carbon dioxide** from the air and soil to form carbonic acid (H_2CO_3). The groundwater becomes acidic and dissolves the calcium carbonate in the bedrock, and seeps or percolates through naturally occurring fractures in the rock. With continual water drainage, the fractures become established passageways. The passageways eventually enlarge and often connect, creating an underground drainage system. Over thousands, perhaps millions of years, these passages evolve into the caves seen today.

During heavy rain or flooding in a well-established karst terrain, very little water flows over the surface in stream channels. Most water drains into the ground through enlarged fractures and sinkholes. This underground drainage system sometimes carries large amounts of water, sand, and mud through the passageways and further erodes the bedrock. Sometimes ceilings fall and passageways collapse, creating new spaces and drainage routes.

Not all solution caves form due to dissolution by carbonic acid. Some caves form in areas where hydrogen sulfide gas is released from the earth's **crust** or from decaying organic material. Sulfuric acid forms when the hydrogen sulfide comes in contact with water. It chemically weathers the limestone, similar to **acid rain**.

The deep cave environment is often completely dark, has a stable atmosphere, and the **temperature** is rather constant, varying only a few degrees throughout the year. The **humidity** in limestone caves is usually near 100%. Many caves contain unique life forms, underground streams and **lakes**, and have unusual mineral formations called speleothems.

When groundwater seeps through the bedrock and reaches a chamber or tunnel, it meets a different atmosphere. Whatever mineral is in solution reacts with the surrounding atmosphere, precipitates out, and is deposited in the form of a crystal on the cave ceiling or walls. Calcite, and to a lesser degree, aragonite, are the most common **minerals** of speleothems. The amount of mineral that precipitates out depends upon how much gas was dissolved in the water. For example, water that must pass through a thick layer of soil becomes more saturated with **carbon** dioxide than water that passes through a thin layer. This charges the water with more carbonic acid and causes it to dissolve more limestone from the bedrock. Later, it will form a thicker mineral deposit in the cave interior as a result.

Water that makes its way to a cave ceiling hangs as a drop. When the drop of water gives off carbon dioxide and reaches chemical equilibrium with the cave atmosphere, calcite starts to precipitate out. Calcite deposited on the walls or floors in layers is called flowstone.

Sometimes water runs down the slope of a wall, and as the calcite is deposited, a low ridge is formed. Subsequent drops of water follow the ridge, adding more calcite. Constant buildup of calcite in this fashion results in the formation of a large sheet-like formation, called a curtain, hanging from the ceiling. Curtain formations often have waves and **folds** in them and have streaks of various shades of off-white and browns. The streakiness results from variations in the mineral and **iron** content of the precipitating solution.

Often, a hanging drop falls directly to the ground. Some calcite is deposited on the ceiling before the drop falls. When the drop falls, another takes its place. As with a curtain formation, subsequent drops will follow a raised surface and a buildup of calcite in the form of a hanging drop develops. This process results in icicle-shaped speleothems called stalactites. The water that falls to the floor builds up in the same fashion, resembling an upside down icicle called a stalagmite.

Of course, there are variations in the shape of speleothems depending on how much water drips from the ceiling, the temperature of the cave interior, rates and directions of air flow in the cave, and how much dissolved limestone the water contains. Speleothems occur as tiered formations, cylinders, cones, some join together, and occasionally **stalactites and stalagmites** meet and form a tower. Sometimes, when a stalactite is forming, the calcite is initially deposited in a round ring. As calcite builds up on the rim and water drips through the center, a hollow tube called a straw develops. Straws are often transparent or opaque and their diameter may be only that of a drop of water.

Stalagmites and stalactites occur in most solution caves and usually, wherever a stalactite forms, there is also a stalagmite. In caves where there is a great deal of seepage, water may drip continuously. Speleothems formed under a steady drip of water are typically smooth. Those formed in caves where the water supply is seasonal may reveal growth rings similar to those of a tree trunk. Stalactites and stalagmites grow by only a fraction of an inch or centimeter in a year, and since some are many yards or meters long, one can appreciate the time it takes for these speleothems to develop.

The most bizarre of speleothems are called helictites. Helictites are hollow, cylindrical formations that grow and twist in a number of directions and are not simply oriented according to the gravitational pull of a water drop. Other influences such as crystal growth patterns and air currents influence the direction in which these speleothems grow. Helictites grow out from the side of other speleothems and rarely grow larger than 4 in (8.5 cm) in length.

Speleothems called anthodites are usually made of aragonite. Calcite and aragonite are both forms of calcium carbonate, but crystallize differently. Anthodites grow as radiating, delicate, needle-like **crystals**. Pools of seepage water that drain leave behind round formations called cave popcorn. Cave pearls are formed in seepage pools by grains of sand encrusted with calcite; flowing water moves the grains about and they gather concentric layers of calcite.

See also Erosion; Stalactites and stalagmites

CAVE MINERALS AND SPELEOTHEMS

Cave minerals are secondary minerals formed inside a cave resulting from one or several of the following processes: reprecipitation of the **bedrock**, supersaturation of solutions, dehydration, biogenic processes (or human activity), **hydrothermal processes**, hypergenic processes (**weathering** or metasomatoze), reaction of karst solutions with minerals of non-karstic bedrock, or by eruptive processes (fumarolic or magmatic) due to crystallization of volcanic gases or their reactions with minerals or solutions.

Most speleothems (dripstones, including stalagmites and **stalactites**) are formed by hydrocarbonate reprecipitation of carbonate bedrock. **Groundwater** saturated with carbonate dioxide dissolves calcium carbonate ($CaCO_3$ from the bedrock and reprecipitates it inside the cave when carbonate dioxide volatilizes. Most caves are developed in **limestone** or **marble**, so $CaCO_3$ forms most speleothems. Ninety-five percent of all speleothems are formed by calcite, 2–3% by aragonite (the second polymorphic form of $CaCO_3$) and less than 2% are formed by the rest of about 250 cave minerals, most frequently **gypsum** (as some caves are developed in gypsum bedrock).

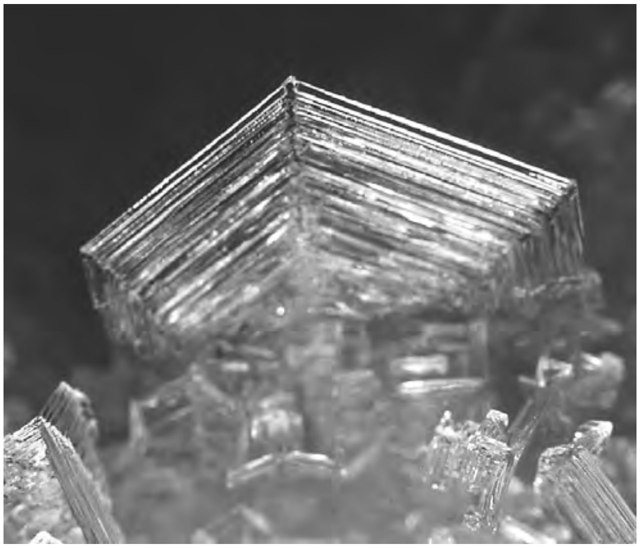
More than 250 different cave minerals have been identified so far. Many are found only in caves, and some are found only in one cave in the world.

Characteristic red luminescence of hydrothermal calcite. *© Y. Shopov. Reproduced by permission.*

Air **temperature** and **humidity** are exceptionally stable in deep parts of caves. This allows preservation of highly unstable minerals and speleothems, which tend to transform and disintegrate within months if taken out of the cave. Such minerals are crystallohydrates with high numbers of **water** molecules. These minerals dehydrate at room air temperature and humidity, and their mineral aggregates disintegrate to powder.

Speleothems are the form of appearance (aggregates) of secondary cave minerals. Aggregates of primary minerals or detrital materials in caves are not speleothems. Most commonly, speleothems grow from the dripping of flowing water. Stalagmites and stalactites are formed by dripping water. Flowstones are smooth and sheet-like speleothems, which form from films of flowing water. Crystal orientation inside flowstones is perpendicular to the surface, and usually has distinctive layers. Shields are oval speleothems consisting of two parallel spherical plates separated by a medial planar crack and are formed by water seeping thought the medial crack. Cave pearls are small spheroidal solid polycrystalline speleothems. Sometimes they are polished by **rotation** due to dripping of water producing turbulent flows in small pools. Thus, they rotate and polish pearls in the pool. Cave pearls resemble real pearls from the sea, but are usually composed of calcite. They become fractured quickly if removed from the cave.

A variety of speleothems grow from cave pools and **lakes**. Rimstones are deposits that form around the bottom and walls of a cave pool. Rimstone dams (gours) are secondarily deposited barriers obstructing flowing of a cave stream or pool. Shelfstones are flat-ledge or shelf-like deposits around the edges of a cave pool or a speleothem submerged in it. Cave rafts are thin layers of crystalline material that float on the surface of a cave pool. Cave bubbles are crystalline material deposited on the surface of a gas bubble in a cave pool.



Large cave ice skeleton crystal in Crow's Nest Pass. © *Y. Shopov. Reproduced by permission.*

Phosphorescence of calcite cave pearls. © *Y. Shopov. Reproduced by permission.*

Bubbles are hollow, with diameters less than 1 cm and have wall thickness of less than 0.2 mm.

Spar is formed by high amounts of water at stable temperature, humidity, and **evaporation** rate. Spar is a speleothem consisting of translucent **crystals** with a vitreous luster, and may be formed by hydrothermal, epithermal or infiltration waters.

Thin films of water form typically form coralloides and anthodites. Coralloides (corallites) are the most common type of speleothem after stalactites, stalagmites, and flowstone. They are nodular, globular or coral-like in shape. Anthodites are speleothems composed of radiating, spiky, quill-like crystal clusters. Frostwork anthodites consist of needle-like crystals. They grow from capillary water moving over the surface of the crystals. Sometimes anthodites are tubular, but never frostwork. Christmas trees are deposits of frostwork over stalagmites.

Helictites are twisted and worm-like speleothems growing via a tiny (0.008–0.5 mm) capillary canal in their center. Helictites twist in any direction, independently of **gravity**. Many helictites resemble a living species. Usually, helictites composed of calcite are transparent, while those of aragonite are composed of bunches of fine crystals, and are opaque.

Cave hair (angel hair) is fibrous speleothem composed of single crystal fibers resembling thin strands of hair. It is formed by gypsum or by highly soluble sulfate or nitrate minerals. Cave hair are very fast growing, but highly unstable (seasonal speleothems), and can be dissolved by increasing of the air humidity or by a heavy rain. Cave flowers are speleothems with crystal petals that curve radially outwards from a common center. They consist of an aggregate of branching and curving bundles of parallel crystals loosely packed together. Cave flowers are usually formed by gypsum. All such fibrous speleothems grow from their base extruding crystals through the pores of the bedrock or **clay** substrate.

Moonmilk is an aggregate of microcrystalline cave minerals precipitated quickly under highly metastable conditions. Moonmilk resembles cream cheese when wet, but is crumbly and powdery like chalk when dry. Cave balloons are pearly, thin-walled, free-hanging speleothems associated with moonmilk substrate resembling a small, inflated balloon. Usually, they are composed wholly or partly of hydromagnesite.

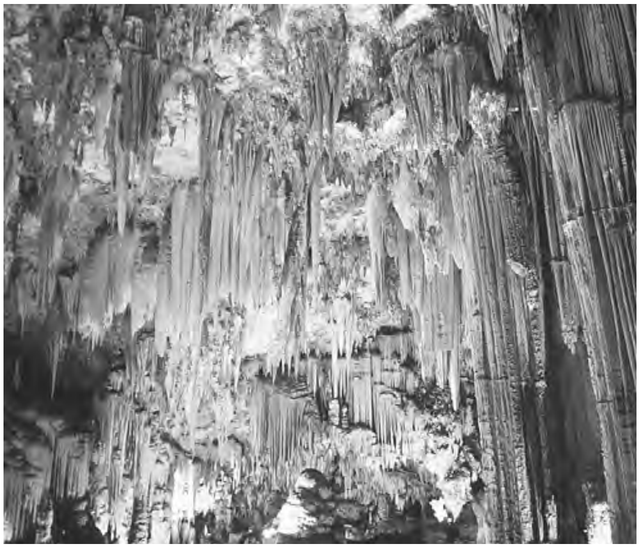
One-hundred and two cave minerals are known to form coatings and crusts, 57 form **stalactites and stalagmites**, 23 form moonmilk, 15 form anthodites, 14 form helictites, 12 form Angel hair, 7 form coralloides and pearls, and 6 form cave balloons.

Cave minerals and speleothems are so unique in appearance that they are considered natural heritage objects, and laws in most countries prohibit their collection, mining and selling.

See also Stalactites and stalagmites

CCD (CARBONATE COMPENSATION DEPTH)

In **oceanography**, the depth where carbonate ions under saturation in the **water** column or in the sediment pore and the water interface is large enough so that the rate of calcium carbonate ($CaCO_3$) **sedimentation** is totally compensated for by the rate of calcium carbonate dissolution, reaches the carbonate compensation depth (CCD). Alternately stated, the CCD is the depth at which calcareous skeletons of marine animals accumulate at the same rate at which they dissolve. Depending on the mineral structure of $CaCO_3$, the CCD is called calcite



Stalactites in Cueva Nerja Cave, Spain. *© Y. Shopov. Reproduced by permission.*

compensation depth (trigonal structure) or aragonite compensation depth (rhombic structure), respectively.

Foraminifera, coccolithophorids, pteropods, and a few other benthic and planktic organisms build calcium carbonate shells or skeletons. Upon death or reproduction, the shells are discarded and sink to the sea-floor. Within the water column, calcium (Ca^{2+}) content varies little, hence the calcium carbonate saturation state (CSS) is controlled by concentration of carbonate (CO_3^{2-}) ions, **pH**, water pressure, **temperature**, and salinity:

$$CSS = (Ca^{2+}) \times (CO_3^{2-}) \div K'_{sp}$$

whereas K'_{sp} is the equilibrium solubility product for the mineral phase of calcite or aragonite, respectively. It is CSS: supersaturated $>$ 1 = saturated = 1 $>$ undersaturated with carbonate ions. Position and thickness of the saturation horizon in the water column can be defined as the difference ΔCO_3^{2-} between the concentration of carbonate ions *in situ* and the concentration of saturated carbonate ion for the respective mineral phase. Since the concentration of carbonate ions cannot be measured directly, it is calculated using the dissociation constants of carbonic acid (H_2CO_3), and measurable parameters such as total inorganic **carbon dioxide** (Σ CO_2) dissolved in sea water, alkalinity, pH, and partial pressure of **carbon** dioxide exerted by sea water (pCO_2).

The water depth at which the sea water carbonate ion content and the concentration of carbonate ions in equilibrium with sea water for calcite or aragonite mineral phase intercept is called hydrographic calcite or aragonite lysocline, respectively. Below the lysocline, calcium carbonate dissolution begins and becomes progressively more intense in proportion to the fourth power of carbonate ion undersaturation. An undersaturation of about 10 µmol/kg is enough to dissolve almost all the calcite descending to the sea floor. At the CCD, the rate of calcium carbonate sedimentation is totally compensated for by the rate of calcium carbonate dissolution. These deepest parts of the global ocean, the **abyssal plains**, where depths exceed about 17,500 feet (4,500 meters), the bottom is no more covered with **calcareous ooze** but with a layer of red-clay that contains no **fossils** at all.

From the surface water as the place of life-history down to the sedimentological archive, diversity of calcareous organism assemblages changes qualitatively and quantitatively due to carbonate dissolution. Each type of calcium carbonate shell architecture yields different crash behavior regarding foraminifera, coccolithophorids, pteropods, and other planktic and benthic calcium carbonate skeleton bearing organisms. For example, planktic foraminifer *Globigerinoides ruber* is rapidly dismantling into single chambers along sutures whereas *Neogloboquadrina pachyderma* is undergoing long lasting ultrastructural breakdown before the final smash. That is, calcium carbonate dissolution is a progress affecting individuals (of any level in Linné's system) in different extent.

Disintegration of calcium carbonate skeleton bearing organisms is a valuable tool to reconstruct modern (i.e., Holocene) and ancient (e.g., Pleistocene) deep and bottom water currents that are traceable through their different CO_2 accumulation. CCD is found deepest in the North Atlantic Ocean (50°N) at about 5,000 m moving upwards continuously in the water column to 3,000 m in the Atlantic sector of the Southern Ocean (60°S) and, in turn, CCD is found deepest in the Pacific sector of the Southern Ocean (60°S) at about 4,500 m moving upwards to 3,000 m in the North Pacific Ocean (50°N). In more general terms, the CCD appears to coincide with the calcium carbonate saturation state of 0.75 in the Atlantic and 0.65 in the Pacific.

Reconstructing CCD of modern and ancient **oceans** means to elucidate the role that oceanic deep-water processes play in global **climate** change during various **geologic time** intervals and at different levels of precision. The location of CCD, lysocline and saturation horizon determine deep water CO_3^{2-} concentrations and thus the pCO_2 of surface waters. Hence, the ocean's ability to take up atmospheric pCO_2 is influenced by the balance of production and dissolution of calcium carbonate, and lifting or lowering the CCD has important consequences on the short and long term variations of CO_2 in the atmosphere.

See also Ocean circulation and currents

CELESTIAL SPHERE: THE APPARENT MOTIONS OF THE SUN, MOON, PLANETS, AND STARS

The celestial sphere is an imaginary **projection** of the **Sun**, **Moon**, planets, stars, and all astronomical bodies upon an imaginary sphere surrounding Earth. The celestial sphere is a useful mapping and tracking remnant of the geocentric theory of the ancient Greek astronomers.

Although originally developed as part of the ancient Greek concept of an Earth-centered universe (i.e., a geocentric model of the Universe), the hypothetical celestial sphere provides an important tool to astronomers for fixing the location and plotting movements of celestial objects. The celestial sphere describes an extension of the lines of **latitude and longitude**, and the plotting of all visible celestial objects on a hypothetical sphere surrounding the earth.

The ancient Greek astronomers actually envisioned concentric crystalline spheres, centered around Earth, upon which the Sun, Moon, planets, and stars moved. Although heliocentric (Sun-centered) models of the universe were also proposed by the Greeks, they were disregarded as “counter-intuitive” to the apparent motions of celestial bodies across the sky.

Early in the sixteenth century, Polish astronomer Nicolaus Copernicus (1473–1543) reasserted the heliocentric theory abandoned by the Ancient Greeks. Although sparking a revolution in **astronomy**, Copernicus’ system was deeply flawed by the fact that the Sun is certainly not the center of the universe, and Copernicus insisted that planetary orbits were circular. Even so, the heliocentric model developed by Copernicus fit the observed data better than the ancient Greek concept. For example, the periodic “backward” motion (retrograde motion) in the sky of the planets Mars, Jupiter, and Saturn, and the lack of such motion for Mercury and Venus was more readily explained by the fact that the former planets’ orbits were outside of Earth’s. Thus, the earth “overtook” them as it circled the Sun. Planetary positions could also be predicted much more accurately using the Copernican model.

Danish astronomer Tycho Brahe’s (1546–1601) precise observations of movements across the “celestial sphere” allowed German astronomer and mathematician **Johannes Kepler** (1571–1630) to formulate his laws of planetary motion that correctly described the elliptical orbits of the planets.

The modern celestial sphere is an extension of the **latitude** and **longitude** coordinate system used to fix terrestrial location. The concepts of latitude and longitude create a grid system for the unique expression of any location on Earth’s surface. Latitudes—also known as parallels—mark and measure distance north or south from the equator. Earth’s equator is designated 0° latitude. The north and south geographic poles respectively measure 90° north (N) and 90° south (S) from the equator. The angle of latitude is determined as the angle between a transverse plane cutting through Earth’s equator and the right angle (90°) of the **polar axis**. Longitudes—also known as meridians—are great circles that run north and south, and converge at the north and south geographic poles.

On the celestial sphere, projections of lines of latitude and longitude are transformed into declination and right ascension. A direct extension of Earth’s equator at 0° latitude is the celestial equator at 0° declination. Instead of longitude, right ascension is measured in hours. Corresponding to Earth’s **rotation**, right ascension is measured from zero hours to 24 hours around the celestial sphere. Accordingly, one hour represents 15 angular degrees of travel around the 360° celestial sphere.

Declination is further divided into arcminutes and arcseconds. In 1° of declination, there are 60 arcminutes (60’) and in one arcminute there are 60 arcseconds (60”). Right ascension hours are further subdivided into minutes and seconds of time.

On Earth’s surface, the designation of 0° longitude is arbitrary, an international convention long held since the days of British sea superiority. It establishes the 0° line of longitude—also known as the Prime Meridian—as the great circle that passes through the Royal National Observatory in Greenwich, England (United Kingdom). On the celestial sphere, zero hrs (0 h) right ascension is also arbitrarily defined by international convention as the line of right ascension where the ecliptic—the apparent movement of the Sun across the celestial sphere established by the plane of the earth’s orbit around the Sun—intersects the celestial equator at the vernal equinox.

For any latitude on Earth’s surface, the extended declination line crosses the observer’s zenith. The zenith is the highest point on the celestial sphere directly above the observer. By international agreement and customary usage, declinations north of the celestial equator are designated as positive declinations (+) and declinations south of the celestial equator are designated as negative declinations (–) south.

Just as every point on Earth can be expressed with a unique set of latitude and longitude coordinates, every object on the celestial sphere can be specified by declination and right ascension coordinates.

The polar axis is an imaginary line that extends through the north and south geographic poles. The earth rotates on its axis as it revolves around the Sun. Earth’s axis is tilted approximately 23.5 degrees to the plane of the ecliptic (the plane of planetary orbits about the Sun or the apparent path of the Sun across the imaginary celestial sphere). The tilt of the polar axis is principally responsible for variations in solar illumination that result in the cyclic progressions of the **seasons**. The polar axis also establishes the principal axis about which the celestial sphere rotates. The projection of Earth’s geographic poles upon the celestial sphere creates a north celestial pole and a south celestial pole. In the Northern Hemisphere, the star Polaris is currently within approximately one degree (1°) of the north celestial pole and thus, from the Northern Hemisphere, all stars and other celestial objects appear to rotate about Polaris and, depending on the latitude of observation, stars located near Polaris (circumpolar stars) may never “set.”

For any observer, the angle between the north celestial pole and the terrestrial horizon equals and varies directly with latitude north of the equator. For example, at 30° N latitude an observer views Polaris at +30° declination, at the terrestrial North Pole (90° N), Polaris would be directly overhead (at the zenith) at +90° declination.

The celestial meridian is an imaginary arc from the north point on the terrestrial horizon through the north celestial pole and zenith that terminates on the south point of the terrestrial horizon.

Regardless of location on Earth, an observer’s celestial equator passes through the east and west points of the terrestrial horizon. In the Northern Hemisphere, the celestial equator is displaced southward from the zenith (the point directly over the observer’s head) by the number of degrees equal to the observer’s latitude.

Rotation about the polar axis results in a diurnal cycle of night and day, and causes the apparent motion of the Sun across the imaginary celestial sphere. The earth rotates about the polar axis at approximately 15 angular degrees per hour and makes a complete rotation in 23.9 hours. This corresponds to the apparent rotation of the celestial sphere. Because the earth rotates eastward (from west to east), objects on the celestial sphere usually move along paths from east to west (i.e., the Sun "rises" in the east and "sets" in the west). One complete rotation of the celestial sphere comprises a diurnal cycle.

As the earth rotates on its polar axis, it makes a slightly elliptical orbital revolution about the Sun in 365.26 days. Earth's revolution about the Sun also corresponds to the cyclic and seasonal changes of observable stars and constellations on the celestial sphere. Although stars grouped in traditional constellations have no proximate spatial relationship to one another (i.e., they may be billions of light years apart) that do have an apparent relationship as a two-dimensional pattern of stars on the celestial sphere. Accordingly, in the modern sense, constellations establish regional location of stars on the celestial sphere.

A tropical year (i.e., a year of cyclic seasonal change), equals approximately 365.24 mean solar days. During this time, the Sun appears to travel completely around the celestial sphere on the ecliptic and return to the vernal equinox. In contrast, one orbital revolution of Earth about the Sun returns the Sun to the same backdrop of stars—and is measured as a sidereal year. On the celestial sphere, a sidereal day is defined as the time it takes for the vernal equinox—starting from an observer's celestial median—to rotate around with the celestial sphere and recross that same celestial median. The sidereal day is due to Earth's rotational period. Because of precession, a sidereal year is approximately 20 minutes and 24 seconds longer than a tropical year. Although the sidereal year more accurately measures the time it takes Earth to completely orbit the Sun, the use of the sidereal year would eventually cause large errors in calendars with regard to seasonal changes. For this reason the tropical year is the basis for modern Western calendar systems.

Seasons are tied to the apparent movements of the Sun and stars across the celestial sphere. In the Northern Hemisphere, summer begins at the summer solstice (approximately June 21) when the Sun is reaches its apparent maximum declination. Winter begins at the winter solstice (approximately December 21) when the Sun's highest point during the day is its minimum maximum daily declination. The changes result from a changing orientation of Earth's polar axis to the Sun that result in a change in the Sun's apparent declination. The vernal and autumnal equinox are denoted as the points where the celestial equator intersects the ecliptic.

The location of sunrise on the eastern horizon, and sunset on the western horizon also varies between a northern most maximum at the summer solstice to a southernmost maximum at the winter solstice. Only at the vernal and autumnal equinox does the Sun rise at a point due east or set at a point due west on the terrestrial horizon.

During the year, the moon and planets appear to move in a restricted region of the celestial sphere termed the zodiac. The zodiac is a region extending outward approximately 8° from each side of the ecliptic (the apparent path of the Sun on the celestial sphere). The modern celestial sphere is divided into twelve traditional zodiacal constellation patterns (corresponding to the pseudoscientific astrological zodiacal signs) through which the Sun appears to travel by successive eastwards displacements throughout the year.

During revolution about the Sun, the earth's polar axis exhibits parallelism to Polaris (also known as the North Star). Although observing parallelism, the orientation of Earth's polar axis exhibits precession—a circular wobbling exhibited by gyroscopes—that results in a 28,000-year-long precessional cycle. Currently, Earth's polar axis points roughly in the direction of Polaris (the North Star). As a result of precession, over the next 11,000 years, Earth's axis will precess or wobble so that it assumes an orientation toward the star Vega.

Precession causes an objects celestial coordinates to change. As a result, celestial coordinates are usually accompanied by a date for which the coordinates are valid.

Corresponding to Earth's rotation, the celestial sphere rotates through 1° in about four minutes. Because of this, sunrise, sunset, moonrise, and moonset all take approximately two minutes because both the Sun and Moon have the same apparent size on the celestial sphere (about 0.5°). The Sun is, of course, much larger, but the Moon is much closer. If measured at the same time of day, the Sun appears to be displaced eastward on the star field of the celestial sphere by approximately 1° per day. Because of this apparent displacement, the stars appear to "rise" approximately four minutes earlier each evening and set four minutes later each morning. Alternatively, the Sun appears to "rise" four minutes earlier each day and "set" four minutes earlier each day. A change of approximately four minutes a day corresponds to a 24-hour cycle of "rising" and "setting" times that comprise an annual cycle.

In contrast, if measured at the same time each day, the Moon appears to be displaced approximately 13° eastward on the celestial sphere per day and therefore "rises" and "sets" almost one hour earlier each day.

Because the earth is revolving about the Sun, the displacement of the earth along it's orbital path causes the time it takes to complete a cycle of lunar phases—a synodic month—and return the Sun, Earth, and Moon to the same starting alignment to be slightly longer than the sidereal month. The synodic month is approximately 29.5 days.

Earth rotates about its axis at approximately 15 angular degrees per hour. Rotation dictates the length of the diurnal cycle (i.e., the day/night cycle), and creates "time zones" with differing local noons. Local noon occurs when the Sun is at the highest point during its daily skyward arch from east to west (i.e., when the Sun is at its zenith on the celestial meridian). With regard to the solar meridian, the Sun's location (and reference to local noon) is described in terms of being ante meridian (am)—east of the celestial meridian—or post meridian (pm) located west of the celestial meridian.

See also Astrolabe; Geographic and magnetic poles; Latitude and longitude; Revolution and rotation; Year, length of

CEMENTATION • *see* LITHIFICATION

CENOZOIC ERA

In **geologic time**, the Cenozoic Era, the third era in the **Phanerozoic Eon**, follows the **Mesozoic Era** and spans the time between roughly 65 million years ago (mya) and present day. On the geologic time scale, Earth is currently in the Cenozoic Era of the Phanerozoic Eon.

The Cenozoic Era contains two geologic time periods, including the **Tertiary Period** (65 mya to approximately 1.8 mya) and the current **Quaternary Period** (1.8 mya to present day). The Tertiary Period is also sometimes referred to in terms of a Paleogene Period and a Neogene Period. When referred to in terms of a Paleogene Period and a Neogene Period, the Paleogene Period extends from approximately 65 mya to 23 mya and the Neogene Period from 23 mya to 2.6 mya. The Quaternary Period is also termed the Anthropogene Period. These periods are further subdivided into six different major epochs, including the **Paleocene Epoch**, **Oligocene Epoch**, **Miocene Epoch**, and **Pliocene Epoch**, **Pleistocene Epoch** and current **Holocene Epoch**.

The onset of the Cenozoic Era is marked by the K-T boundary or K-T event—the mass extinction of non-avian dinosaurs marking the boundary between the **Cretaceous Period** of the Mesozoic Era and the Tertiary Period of the Cenozoic Era.

At the start of the Cenozoic Era, **North America** and **Europe** were separated by a widening ocean basin spreading along a prominent mid-oceanic ridge. North America and **South America** were separated by a confluence of the future Pacific Ocean and Atlantic Ocean, and extensive flooding submerged much of what are now the eastern and middle portions of the United States. By start of the Cenozoic Era, **water** separated South America from **Africa**, and seafloor spreading continued to push the continents apart. The Australian and Antarctic continents were clearly articulated and the Antarctic continent had begun a southward migration toward its present position in the south polar region. At the outset of the Cenozoic Era, the Indian plate and subcontinent remained far south of the Eurasian plate and continent.

By 30 mya, the modern continental arrangement was easily recognizable. Although still separated by water, the land bridge between North and South America began to reemerge. **Antarctica** assumed a polar position and extensive **ice** accumulation began on the continent. The Indian plate drove rapidly northward of the equator to close with the Eurasian plate. Although still separated by a shallow straight of water, the impending collision of the plates that would eventually form the Himalayan mountain chain had begun. The gap between North America and Europe continued to widen at a site of **seafloor spreading** along a prominent mid-Atlantic ridge. By mid-Tertiary Period, the mid-Atlantic ridge was apparent in a large suture-like extension into the rapidly widening South Atlantic Ocean that separated South America from Africa.

Well into the Cenozoic Era, by the start of the Quaternary Period some 2.6 million years ago, Earth's continents assumed their modern configuration. The Pacific Ocean separated **Asia** and **Australia** from North America and South America, the Atlantic Ocean separated North and South America from Europe (Euro-Asia) and Africa. Separated by the straits of Indonesia, the Indian Ocean filled the basin between Africa, India, Asia, and Australia. The Indian plate driving against and under the Eurasian plate uplifted rapid mountain building. As a result of the collision, ancient oceanic **crust** bearing marine **fossils** was uplifted into the Himalayan chain. The collision between the Indian and Eurasian plate continues with a resulting slow—but measurable—increase in the altitude of the highest Himalayan Mountains (e.g., Mt. Everest) each year. Although glacial sheets advance and recede in cyclic patterns (i.e., reestablish new terrain altering ice ages, the basic patterns of **glaciation** evident today were established during the Quaternary Period.

Many geologists and paleontologists assert that the K-T extinction resulted from a cataclysmic asteroid impact in an **area** now located underwater near the Yucatan Peninsula of Mexico. The impact caused widespread primary damage due to the blast impact and firestorms. The major damage to Earth's ecosystem occurred when the debris and smoke from the collision and subsequent fires moved into the atmosphere to block a sufficient amount of light from the **Sun** that photosynthesis was greatly slowed. The resulting climatic changes and food shortages led to extinction of the largest life forms (those with the greatest energy needs), including the dinosaurs.

Although mammals evolved before the Cenozoic Era, the reduction in predator species allowed land mammals to dominate and thrive—eventually setting the stage from the **evolution** of homo sapiens (humans).

See also Archean; Cambrian Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Jurassic Period; Mississippian Period; Ordovician Period; Paleozoic Era; Pennsylvanian Period; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Supercontinents; Tertiary Period; Triassic Period

CENTIGRADE SCALE • *see* TEMPERATURE AND TEMPERATURE SCALES

CHALCOPHILES, LITHOPHILES, SIDEROPHILES, AND ATMOPHILES

Chalcophiles, lithophiles, siderophiles, and atmophiles are classes of elements based upon similar geochemical properties and reactive affinities. The classes were originally advanced by Swiss-born **Victor Goldschmidt** (1888–1947) and are terms still widely used by geologists and geochemists. The key factor in determining an element's class is the type of **chemical bonds** that the element forms.

Chalcophile elements have a high bonding affinity—usually in the form of covalent bonds—with sulfur, and are, accordingly, usually abundant in sulfides. Chalcophiles also exhibit a bonding affinity with selenium, tellurium, arsenic, and antimony and therefore also exhibit high levels of derivatives of these elements. When sulfur is abundant, chalcophile elements readily form sulfide **minerals** as they precipitate from the **magma**. This process partially explains the formation of extensive deposits of iron-nickel-copper sulfides.

Lithophiles have a high bonding affinity with **oxygen**. Lithophiles have an affinity to form ionic bonds and are represented by silicates (**silicon** and oxygen) in the **crust** and mantle. Other lithophile elements include magnesium, **aluminum**, sodium, potassium, **iron**, and calcium.

Siderophiles exhibit a weak affinity to both oxygen and sulphur. Siderophiles have an affinity for iron and a distinguishing characteristic of siderophiles is that they exhibit high solubility in molten iron. Siderophile elements generally have a low reactivity and exhibit an affinity to form metallic bonds. As a result, siderophiles are most often found in their native state. Not abundant in the core or mantle, most siderophiles are thought to be richest at Earth's core. Platinum (Pt) group **metals,** including Ruthium (Ru), Rhodium (Rd), Palladium (Pd), Osmium (Os), and Iridium (Ir), show exhibit a strong siderophile tendency.

Atmophiles are a related fourth class of elements characterized by their ability to form van der Waals bonds. Atmophiles are also highly volatile.

Chalcophiles, lithophiles, siderophiles, and atmophiles have differing densities. Accordingly, after formation from the molten state, these differential densities tend to separate the classes. For example, siderophiles have a greater average density than lithophiles and thus lithophiles would tend to "rise" in the molten state relative to siderophiles. Although the element classes were derived, in part, from an attempt to explain the distribution of elements, the density differences do not always result in the expected distribution of classes in the earth's core, mantle and crust.

Because geochemical reactivity is a function of electron structure—especially the number of electrons available for bonding—element classes tend to follow groupings or trend as related to the **periodic table**. The difference in the classification of elements can also be linked to differing valence states.

It is possible for some elements to be assigned to more than one group. The reactivity of an element can also be driven by the relative amounts of elements surrounding it. For example, iron, when in an oxygen deprived environment (e.g., at the earth's core) acts as a siderophile. In the more oxygen rich environment of the crust and mantle, iron acts as a lithophile or chalcophile, and in this form is commonly found in **igneous rocks**. When sulfur is present is found in sulfide deposits. Siderophiles when surrounded by sulfur, arsenic, and antimony may act as chalcophiles.

See also Chemical bonds and physical properties; Chemical elements

CHALLENGER EXPEDITION

The British Navy vessel H.M.S. *Challenger* circumnavigated the world between December 1872 and May 1876, conducting history's first systematic, scientific investigation of the world's **oceans**. The *Challenger* expedition gathered a body of data that has been matched by few voyages of discovery. The science of modern **oceanography** essentially began with the *Challenger* expedition.

The *Challenger* was a 200 foot (67 m), three-masted, square-rigged wooden sailing ship equipped with an auxiliary steam engine. Fifteen of its 17 gun bays were rebuilt as laboratories, workrooms, and storage spaces for scientific equipment. It carried a crew of five scientists, an official artist, 20 officers, and about 200 sailors.

The *Challenger* began its voyage by crossing the Atlantic four times, discovering the Mid-Atlantic Ridge in the process. It then visited **Africa**, **Antarctica**, New Zealand, New Guinea, China, Japan, Hawaii, the South **Seas**, and the tip of **South America**, studying not only the sea itself but the fauna, flora, and geography of numerous islands. The *Challenger* team made 362 regularly-spaced midocean measurements of depth, **temperature**, and currents and used special dredges to collect samples of life, ooze, and rocks from the ocean floor. This expedition produced the first global cross-section of the ocean's depth profile and identified over 4,700 ocean-dwelling animal species never before known.

The *Challenger* returned triumphantly to **Europe** freighted with tens of thousands of photographs, drawings, measurements, and biological and geological samples. Publication of the results took 20 years and required 50 thick volumes totaling almost 30,000 pages. Data from the *Challenger* expedition are still cited occasionally in modern scientific literature.

A century after the first *Challenger* expedition, the research drillship *Glomar Challenger* (1968–1983) cruised the world's oceans gathering data that were also to prove revolutionary for Earth sciences. Its deep-sea core samples confirmed the theory of continental drift and revealed for the first time that the oceanic **crust** is extremely young compared to the continental crust.

See also Deep sea exploration

CHANNEL PATTERNS

Channel patterns are types of sedimentary deposits formed by streams and **rivers**. Collectively, they are called fluvial deposits. Their shape and sediment characteristics are easily identified and enormously complex. Understanding of fluvial deposits is essential to economic **geology** because many of these ancient deposits are a good source of **petroleum**. Extremely old fluvial deposits are found extensively on land and often indicate much different environments. For example, a large river deposit is located outside of Flagstaff, Arizona where there now exists nothing but high **desert**. There is no indication of the source of vast channel cuts, **sand** bars, point bars, and cut banks seen captured in the sediments.

In order to understand and identify channel deposits, the types and natures of streams and rivers must first be learned. Each river has its own unique settings in which it flowed. No

Channel pattern of the Niger River, Timbuktu, Mali. © *Wolfgang Kaehler. UPI/Corbis-Bettmann. Reproduced by permission.*

two rivers have ever been the same. There are some general characters of rivers, however, that are easily observed. Rivers that originate and flow down steep slopes are usually straight and deep compared to a meandering river that flows across relatively flat ground. Meanders are wide curves in rivers that follow the path of least resistance along plains and valleys. In aerial view, the sinuous curves seem to wander over the **topography**. This wavy appearance gives rise to their name meandering rivers. Braided channels occur where steep rivers meet flat lying valleys. Their river's sediment load is rapidly dumped, building a flat surface along which the **water**, previously contained in a single channel, spreads out forming a series of interlocking shallow channels. The channels cut back and forth across the flat plain that gains them the name "braided" channels. The final large type of river group is the anastomosing river where different channels of the river are separated by permanent alluvial islands. From the air, the rivers have many channels that eventually coalesce to form one large possibly meandering river.

The effect of these variable types of waterways is a wide variety of sedimentary deposits. All the depositional types are a result of the increase and decrease of the force of flowing water. As velocities change, so does the sediment-carrying capacity of the water. The stronger the velocity of water, as in a steep channel, the greater the size and amount of sediment the river can transport. Large boulders are not often moved unless storm conditions exist where velocities can reach dangerous levels. Even cobble-sized stones need immense water velocities to be moved. However, sand and silt are much more easily moved along river bottoms. Many studies on the **physics** of water and its carrying capacity have produced information from which geologists can infer the amount of water in a channel at a particular time in history.

Channel bars are longitudinal deposits of mostly sand that accumulates in the centers of rivers. Their development is constant as new sands accumulate on top of old. The moving water is constantly rolling sand grains along the bottoms of rivers and on top of bars. Because the bars have elevation in the rivers, they act as a sort of brake for the water. When the water slows down as it moves around the bars, it deposits its load of sand, increasing the size of the bar and further slowing the water. To further complicate the picture, the channel bottom acts as a drag on the water column. The rough surface of the sand creates friction and slows the water immediately above it while the surface of the water is not slowed. The result is that lighter sediments not lying near the bottom are carried farther and longer in the water column and down the river.

Bars are rarely composed of any sediment larger than sand-sized particles. No type of sand bars is stable. They can migrate over the bottom surface of the channel with changing **seasons** and water flows. The bars can migrate from side to side in the channel and down the river as the water carries more sediment over their tops. When covered by additional sediment, these bars are buried in the channel and remain as a geological facies (specific identifiable geological pattern).

Meanders in rivers produce a variety of fluvial structures. As the water flows along in a meander, the point at which it first hits a turn in the river course receives the most force from the water. As the water continually strikes this bank, it erodes the sediments in front of it. A sharp and well-excavated corner is formed and appropriately called the cutbank. As the water turns the corner, most of its force is absorbed by the cutbank and it loses much of its velocity around the bend. At this point in the semi-circular water pattern, the water has the least velocity and unloads its sediment. The result is a build-up of sand called a point bar. Point bars will often have finer sediments than channel bars because the water loses so much velocity on the outer edges of the point bar that it cannot hold anything but the finest grained particles or clasts.

Because the water now has so little velocity, its course is easily turned sideways where it regains velocity and begins another meander. From the air, a meandering river is an extraordinary view since all the previous channels and turns can be seen as a result of this depositional pattern of cutbanks, channels bars, and point banks. Older and more massive rivers, such as the Mississippi, have an extensive history that is easily seen from an airplane.

As a meandering river ages, it develops interesting features called oxbow **lakes**. The cutting of the banks around the corners continues until one bank nearly touches the other. It looks something like an omega sign (Ω) from the Greek alphabet. Eventually the corners cut enough land away to meet. When this happens, the flow of the river is stronger where the channel is straighter. As a result, the river takes a new course. The abandoned meander does not receive any new sediment and the remaining water is sealed by new point bank bars along the new course. The unique lake that is formed is named an oxbow lake. The lake will eventually fill and die. Trees may overgrow it and a whole new cycle of river meandering leaves it stranded until the river cuts its way back.

These sedimentary structures are just a few of the interesting patterns formed by rivers and streams. They are found in a large range of size scales and are important to geologists worldwide.

See also Petroleum, detection; Stream valleys, channels, and floodplains

CHAOS THEORY (METEOROLOGICAL ASPECTS)

Chaos theory attempts to identify, describe, and quantify order in apparently unpredictable and/or highly complex systems (i.e., atmospheric dynamics, **weather** systems, etc.) in which, out of seemingly random, disordered (e.g., aperiodic) processes there arise processes that are deterministic and predictable.

Complex phenomena are those generally regarded as having too many variables (or too many possible conditions or states) to yield to conventional quantitative analysis. The motion of molecules in swirling smoke or the turbulent hydraulics of a river current, for example, are systems that exhibit such chaotic complexity.

According to the laws of thermodynamics, all natural processes—when considering both system and surroundings—exhibit a tendency toward net movement from the ordered state to a more the chaotic (disordered) state. Conversely, according to some chaos theory models, chaotic, unpredictable, and irreversible processes may, evolve into or produce ordered states. Entropy is a measure of thermodynamic equilibrium used to explain irreversibility in physical and chemical processes. The second law of thermodynamics specifies that in an isolated system, increasing entropy corresponds to changes in the system over time and that entropy tends toward (a statistical mechanical concept) maximization. The second law of thermodynamics dictates that in natural processes, without work being done on a system, there is a movement from order to disorder.

Because entropy in natural processes increases over time, even very straightforward linear-type relationships must eventually take on a degree of irregularity (i.e., of seemingly disordered complexity). In accord with the second law of thermodynamics, apparently chaotic phenomena arise from initially ordered (i.e., lower entropy) systems. This dual tendency toward increasing entropy and chaos from an initially stable state can take place spontaneously. Small perturbations in initial conditions intensify these tendencies. Chaos theorists describe such departures as the butterfly effect.

The study of such mathematical irregularities involving chaos and order remained a relatively unnoticed corner of advanced mathematics until the advent of the digital computer. In 1956, Edward Lorenz, a professor of **meteorology** at the Massachusetts Institute of Technology was studying the numerical solution to a set of three differential equations in three unknowns, a highly simplified version of the types of equations meteorologists then in use to describe atmospheric phenomena. Lorenz came to the conclusion that his set of differential equations displayed a sensitive dependence on initial conditions, a sensitivity of the same type that French mathematician Jules-Henri Poincaré (1854–1912) had discovered for the Newtonian equations when those equations were applied to celestial dynamics. Lorenz, however, gave this phenomenon a new and highly appealing name, the butterfly effect, suggesting that, in the extreme, the flapping of a butterfly's wings in Kansas might be responsible for a monsoon in India a month later.

Along with quantum and relativity theories, chaos theory—with its inclusive concepts of chaos and order—is widely regarded as one of the great intellectual leaps of the twentieth century. The modern physical concepts of chaos and order, however, actually trace their roots to classical mechanical concepts introduced in English physicist Sir Isaac Newton's (1642–1727) 1686 work, *Philosophy Naturalis Principia Mathematica* (Mathematical principles of natural philosophy). It was Newton, one of the inventors of the calculus, who revolutionized **astronomy** and **physics** by showing that the behavior of all bodies, celestial and terrestrial, was governed by the same laws of motion, which could be expressed as differential equations. These differential equations relate the rates of change of physical quantities to the values of those quantities themselves. Such calculated predictability of physical phenomena led to the concept of a mechanistic, clockwork universe that operated according to deterministic laws. The idea that the universe operated in strict accord with physical laws was profoundly influential on science, philosophy and theology.

Most physical models are devoted to the understanding of simple systems (e.g., kinetic molecular theories often rely on concepts related to a ball bouncing in a box). From fundamental laws, using easily quantifiable behavior of such simple systems, theorists often attempt to project the behavior of more complex systems (e.g., the collision and dynamics of hundreds of balls bouncing in a box). It was long thought by physicists that, with regard to these types of models, the complexity of a system simply veiled an underlying fundamental simplicity.

For example, according to classical deterministic concepts, the accurate analysis and prediction of complex systems (e.g., the determination of the momentum of a particular ball among hundreds of other balls bouncing and colliding in a box) could be calculated only if the initial or starting conditions were accurately known. The fact that it is usually impossible to predict the exact condition or behavior of a system (especially considering that such interactions or measurements of a systems must also alter the system itself) is usually explained away as the result of a lack of knowledge regarding starting conditions or a lack of calculating vigor (e.g., inadequate computing power).

See also Atmospheric circulation; Weather forecasting methods; Weather forecasting

CHATOYENCY • *see* GEMSTONES

CHEMICAL BONDS AND PHYSICAL PROPERTIES

Chemical bonds are the electrical forces of attraction that hold atoms or ions together to form molecules. Different types of chemical bonds and their varying intensity are directly responsible for some of the physical properties of **minerals** such as hardness, **melting** and boiling points, solubility, and conductivity. Chemical bonds also influence such other properties as crystal symmetry and cleavage. Stronger bonds between atoms make them more difficult to separate and, in general, stronger chemical bonds result in greater hardness, higher melting and boiling points, and smaller coefficients of expansion. There are four principal types of chemical bonds found in minerals: ionic, covalent, metallic, and van der Waals.

An ionic bond is the result of the electrostatic attraction between two oppositely charged ions. Ionic bonds exist because some elements tend to capture or lose one or more electrons resulting in a net positive or negative charge. These are called ions. An ion that bears a positive charge is a cation. One with a negative charge is an anion. Ions may carry a single charge, such as Na^+ and Cl^-, or may have multiple charges, such as Ca^{2+} or Fe^{3+}. Oppositely charged ions tend to attract one another because the cation can transfer electrons to the anion, allowing each ion to achieve better stability. For example, Na^+ and Cl^- readily combine to form NaCl, halite (salt). Most minerals are held together by some form of ionic bond.

In order for an ionically bonded solid to melt, some of the bonds, but not all of them, must be broken. For boiling to occur, all of the bonds must be broken. As a result, ionic bonds produce moderate to high melting and boiling points. Ionic bonds are moderate in strength and so result in moderately hard minerals. The electrical conductivity is generally low and minerals with ionic bonds tend to dissolve better in **water**. In addition, because the charge on ions is evenly distributed around the surface of the **atom**, or nondirectional, a cation tends to evenly distribute as many anions as possible over its entire surface **area**. This often yields a high degree of crystal symmetry in minerals. Halite (salt) and fluorite are two common ionically bonded minerals.

Covalent bonds are different from ionic bonds in that electrons are shared between atoms of similar charge as opposed to electrons being donated by a cation to an anion. Covalent bonds form when the electron **clouds** of separate atoms draw near and overlap, enabling electrons to be shared. In covalent bonds, each participating atom usually contributes electrons, resulting in a strong bond. Covalent bonds are common between atoms and ions of the same element such the noble gasses.

Minerals with covalent bonds tend to be hard and insoluble. **Diamond** is one example. Covalent bonds produce high melting and boiling points and low conductivities. The forces that bind the atoms tend to be localized in the vicinity of the shared electrons and so are highly directional. This often yields a lower degree of crystal symmetry.

As the name suggests, metallic bonds are found in pure metallic minerals. Metallic bonds form when an atom of a metallic element, which usually contains loosely held electrons in the outer shell, shares these electrons with closely packed atoms of the same element. The shared electrons pass freely among all the metal atoms. The result may be described as a weak covalent bond. It is different from the true covalent bond, however, in that there are too few electrons to be shared continuously by all atoms simultaneously. The electrons are extremely mobile as they roam within the lattice of positive metal ions. The mobility of the electrons results in the high thermal and electrical conductivity of **metals**. The weakness of the bonds results in the lower hardness, low melting and boiling points, and high ductility so often observed in metallic minerals such as gold and copper.

Van der Waals bonds arise from very minor charge polarities that can develop on molecules that are already bonded together. For example, the directional characteristic of covalent bonds can produce a weak negative charge where the electron clouds overlap with a corresponding weak positive charge opposite the area of overlap. These dipoles may attract each other to form a very weak chemical bond known as Van der Waals. Van der Waals bonds are not common in minerals, but when present result in low hardness and easily cleaved zones. **Graphite** owes its greasy feel to the Van der Waals forces that link sheets of covalently bonded **carbon** atoms, allowing them to easily slip apart.

Most minerals are held together by a combination of chemical bonds. Often, distinct molecular units, consisting of strongly bonded atoms, are linked by weaker bonds, as in the graphite example above. Micas, which cleave perfectly into sheets, are another example. They are composed of covalent-bonded silica tetrahedral sheets joined together by ionic bonds. The ionic bonds tend to break first, separating into the more robust sheets. A single chemical bond in a mineral may also display the properties of more than one bond type. A common example is the silica tetrahedron, which consists of one **silicon** atom, Si^{+4}, surrounded by four **oxygen** atoms, O^{-2}. The bond that binds silicon and oxygen together arises out of an ionic attraction, but it also involves overlapping electron clouds and subsequent sharing of electrons, so it is part covalent as well.

See also Atomic structure; Chemical elements; Crystals and crystallography

CHEMICAL ELEMENTS

By the end of the nineteenth century, the elements and matter comprising all things could no long be viewed as immutable. The dramatic rise of scientific methodology and experimentation during the later half of the eighteenth century set the stage for the fundamental advances in **chemistry** and **physics** made during the nineteenth century. In less than a century, European society moved from an understanding of the chemical elements grounded in mysticism to an understanding of the relationships between elements found in a modern **periodic table**. During the eighteenth century, there was a steady march of discovery with regard to the chemical elements. Isolations of hydrogen and **oxygen** allowed for the formation of **water** from its elemental components. Nineteenth century scientists built experiments on new-found familiarity with elements such as nitrogen, beryllium, chromium and titanium.

By the mid-nineteenth century, chemistry was in need of organization. New elements were being discovered at an increasing pace. Accordingly, the challenge for chemists and physicists was to find a key to understand the increasing volume of experimental evidence regarding the properties of the elements. In 1869, the independent development of the periodic law and tables by the Russian chemist **Dmitry Mendeleev** (1834–1907) and German chemist Julius Meyer (1830–95) brought long sought order and understanding to the elements.

Mendeleev and Meyer did not work in a vacuum. English chemist J.A.R. Newlands (1837–1898) had already published several works that ventured relationships among families of elements, including his “law of octaves” hypothesis. Mendeleev’s periodic chart of elements, however, spurred important discoveries and isolation of chemical elements. Most importantly, Mendeleev’s table provided for the successful prediction of the existence of new elements and these predictions proved true with the discovery of gallium (1875), scandium (1879) and germanium (1885).

By the end of the nineteenth century, the organization of the elements was so complete that British physicists Lord Rayleigh (born John William Strutt, 1842–1919) and William Ramsay (1852–1916) were able to expand the periodic table and to predict the existence and properties of the noble gases argon and neon.

Nineteenth century advances were, however, not limited to mere identification and isolation of the elements. By 1845, German chemist Adolph Kolbe (1818–84) synthesized an organic compound and, in 1861, another German chemist Friedrich Kekule(1829–1896) related the properties of molecules to their geometric shape. These advances led to the development of wholly new materials (e.g., plastics, celluloids) that had a dramatic impact on a society in midst of industrial revolution.

The most revolutionary development with regard to the elucidation of the elements during the nineteenth century came in the waning years of the century. In 1895, Wilhelm Röntgen (1845–1923) published a paper titled: “On a New Kind of Rays.” Röntgen’s work offered the first description of x rays and offered compelling photographs of photographs of a human hand. The scientific world quickly grasped the importance of Röntgen’s discovery. At a meeting of the French Academy of Science, Henri Becquerel (1852–1908) observed the pictures taken by Röntgen of bones in the hand. Within months Becquerel presented two important reports concerning “uranium rays” back to the Academy. Becquerel, who was initially working with phosphorescence, described the phenomena that later came to be understood as **radioactivity**. Less than two years later, two other French scientists, Pierre (1859–1906) and **Marie Curie** (born in Poland, 1867–1934) announced the discovery of the radioactive elements polonium and radium. Marie Curie then set out on a systematic search for radioactive elements and was able, eventually, to document the discovery of radioactivity in uranium and thorium **minerals**.

As the nineteenth century drew to a close, Ernest Rutherford (1871–1937), using an electrometer, identified two types of radioactivity, which he labeled alpha radiation and beta radiation. Rutherford actually thought he had discovered a new type of x ray. Subsequently alpha and beta radiation were understood to be particles. Alpha radiation is composed of alpha particles (the nucleus of helium). Because alpha radiation is easily stopped, alpha radiation-emitting elements are usually not dangerous to biological organisms (e.g., humans) unless the emitting element actually enters the organism. Beta radiation is composed of a stream of electrons (electrons were discovered by J. J. Thomson in 1897) or positively charged particles called positrons.

The impact of the discovery of radioactive elements produced immediate and dramatic impacts upon society. Within a few years, high-energy electromagnetic radiation in the form of x rays, made possible by the discovery of radioactive elements, was used by physicians to diagnose injury. More importantly, the rapid incorporation of x rays into technology established a precedent increasingly followed throughout the twentieth century. Although the composition and nature of radioactive elements was not fully understood, the practical benefits to be derived by society outweighed scientific prudence.

Italian scientist Alessandro Volta's (1745–1827) discovery, in 1800, of a battery using discs of silver and zinc gave rise to the voltaic pile or the first true batteries. Building on Volta's concepts, English chemist Humphry Davy (1778–1829) first produced sodium from the electrolysis of molten sodium hydroxide in 1807. Subsequently, Davy isolated potassium, another alkali metal, from potassium hydroxide in the same year. Lithium was discovered in 1817.

Studies of the spectra of elements and compounds spawned further discoveries. German chemist Robert Bunsen's (1811–1999) invention of the famous laboratory burner that bears his name allowed for the development of new methods for the analysis of the elemental structure of compounds. Working with Russian-born scientist Gustav Kirchhoff (1824–1887) Bunsen's advances made possible flame analysis (a technique now commonly known as atomic emission **spectroscopy** [AES]) and established the fundamental principles and techniques of spectroscopy. Bunsen examined the spectra (i.e., component colors), emitted when a substance was subjected to intense flame. Bunsen's keen observation that flamed elements that emit light only at specific wavelengths—and that each element produces a characteristic spectra—along with Kirchhoff's work on black body radiation set the stage for subsequent development of **quantum theory**. Using his own spectroscopic techniques, Bunsen discovered the elements cesium and rubidium.

Using the spectroscopic techniques pioneered by Bunsen, other nineteenth century scientists began to deduce the chemical composition of stars. These discoveries were of profound philosophical importance to society because they proved that Earth did not lie in a privileged or unique portion of the universe. Indeed, the elements found on Earth, particularly those associated with life, were found to be commonplace in the cosmos. In 1868, French astronomer P.J.C. Janssen (1824–1907) and English astronomer, Norman Lockyer (1836–1920), used spectroscopic analysis to identify helium on the **Sun**. For the first time an element was first discovered outside the confines of Earth.

See also Atomic mass and weight; Atomic number; Big Bang theory; Stellar life cycle

CHEMISTRY

Chemistry deals with the study of the properties and reactions of atoms and molecules. In particular, chemistry deals with reaction processes and the energy transition. Major divisions of chemistry include inorganic chemistry, organic chemistry (chemistry of **carbon** based compounds), physical chemistry, analytical chemistry, and biochemistry. **Geochemistry** deals with the reaction unique to geological processes.

The origin of the modern science of chemistry is often attributed to the work of French physicist and chemist Antoine Lavoisier (1743–1794). In 1774, Lavoisier demonstrated that **oxygen** is a critical component of air needed for combustion. This observation led into a better understanding of the changes in composition and structure of matter. Lavoisier's publication of the first list of elemental substances eventually evolved into the **Periodic table** of the elements. Other important contributions to early chemistry include British chemist and physicist John Dalton's (1766–1844) **atomic theory**; Italian physicist and chemist Amedeo Avogadro's (1776–1856) theory that molecules are made up of atoms; and Sir Edward Frankland's (1825–1899) descriptions of chemical reactions. These observations and theories all led to the portrayal of chemistry as the architecture of molecules.

Each discipline of chemistry (e.g., inorganic, analytical, physical chemistry, etc.) studies a different facet of the structure and composition of materials and their changes in composition and energy. As molecules and scientific problems become more complex, the traditional areas of chemical investigation begin to overlap with other physical sciences.

Organic chemistry is the study of compounds that contain carbon atoms. The term organic was first introduced by the Swedish scientist, Jöns Jacob Berzelius (1779–1848) to refer to substances isolated from living systems. Inorganic compounds, a call predominant in geological processes, are those isolated from nonliving sources. At the time, it was believed that a "vital force" only present in living systems was necessary for the preparation of organic compounds. In 1828, German chemist Friedrich Wöhler (1800–1882) first synthesized urea, an organic compound isolated from urine, by evaporating a **water** solution of the inorganic compound ammonium cyanate. Eventually, the vital force theories (e.g., those based on the idea that life and the chemistry of life depended upon an undefined vital force peculiar to living organisms) were discarded and organic chemistry became the investigation of the over seven million carbon-containing compounds. Today, organic chemists work primarily to synthesize new molecules to be used in pharmaceuticals, surfactants, paints, and coatings. They are also involved in scaling reactions from grams to tons in industrial research laboratories.

Inorganic compounds, at the time of the vital force theories, were those materials isolated from nonliving sources. Now, inorganic chemistry is the chemistry of all the elements except for carbon. This includes the chemistry of transition **metals** which coordinate with organic ligands and make up hemoglobin; the very reactive alkali metals used to make organometallic compounds in the manufacture of pharmaceutical materials; and also, the semi-metallic elements that have unusual electronic properties used in solar cells for the conversion of light into **electricity**. Inorganic chemists find employment in the production of **glass**, ceramics, semi-conductors, and advanced synthetic catalysts.

In 1909, German scientist Wilhelm Ostwald (1853–1932) was awarded the Nobel Prize in Chemistry for his work with catalysis, a very useful technique in industrial manufacturing. Ostwald is often referred to as the father of physical chemistry, a branch of chemistry devoted to the investigation of the underlying physical processes responsible for chemical properties and phenomena. Physical chemistry describes the influence of **temperature**, pressure, concentration, and catalyst used in organic and inorganic reactions. These data give important insight into the mechanisms of the chemical change and predict the best experimental methodology for a specific manufacturing process. Physical chemists are employed in industrial, academic, and governmental laboratories to study and calculate the fundamental properties of elements and molecular compounds. The application of physical chemistry is critical to the development of efficient devices, new applications of chemicals and better methods for measuring chemical phenomena.

Analytical chemistry is the branch of chemistry involved with the measurement and characterization of materials. Chemical analysis is divided into classical and instrumental methods. Wet or classical chemical analysis is the oldest form of analytical chemistry and involves the use of chemical reactions utilizing gravimetric and volumetric methodology to analyze material compositions. The use of instrumental methods for analytical analysis provides comprehensive information about chemical structure. Instrumental techniques include methods for measuring molecular **spectroscopy** such as infrared spectroscopy (IR), nuclear magnetic resonance spectroscopy (NMR), mass spectroscopy (MS), and x-ray crystallography. Gas chromatography, liquid chromatography, and electrophoresis are examples of separation methods used by analytical chemists. There is a need for analytical chemists in governmental, industrial, and academic research organizations to characterize new materials and determine the chemical composition of materials.

Chemists often work with geologists and geophysicists, in an effort to identify specific geologic reactions or to help characterize a specific geologic formation.

See also Atmospheric chemistry; Bowen's reaction series; Dating methods; Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Weathering and weathering series

CHEMOAUTOTROPHIC AND CHEMOLITHOTROPHIC BACTERIA AS WEATHERING AGENTS

The inorganic processes associated with chemoautotrophic and chemolithotrophic bacteria may make these bacteria one of the most important sources of **weathering** and **erosion** of rocks on Earth.

Autotrophic bacteria obtain the **carbon** that they need to sustain survival and growth from **carbon dioxide** (CO_2). To process this carbon source, the bacteria require energy. Chemoautotrophic bacteria and chemolithotrophic bacteria obtain their energy from the oxidation of inorganic (non-carbon) compounds. That is, they derive their energy from the energy already stored in chemical compounds. By oxidizing the compounds, the energy stored in **chemical bonds** can be utilized in cellular processes. Examples of inorganic compounds that are used by these types of bacteria are sulfur, ammonium ion (NH^{4+}), and ferrous **iron** (Fe^{2+}).

The designation autotroph means "self nourishing." Indeed, both chemoautotrophs and chemolithotrophs are able to grow on medium that is free of carbon. The designation lithotrophic means "rock eating," further attesting to the ability of these bacteria to grow in seemingly inhospitable environments.

Most bacteria are chemotrophic. If the energy source consists of large chemicals that are complex in structure, as is the case when the chemicals are derived from once-living organisms, then it is the chemoautotrophic bacteria that utilize the source. If the molecules are small, as with the elements listed above, they can be utilized by chemolithotrophs.

Only bacteria are chemolithotrophs. Chemoautotrophs include bacteria, fungi, animals, and protozoa.

There are several common groups of chemoautotrophic bacteria. The first group is the colorless sulfur bacteria. These bacteria are distinct from the sulfur bacteria that utilize sunlight. The latter contain the compound chlorophyll, and so appear colored. Colorless sulfur bacteria oxidize hydrogen sulfide (H_2S) by accepting an electron from the compound. The acceptance of an electron by an **oxygen atom** creates **water** and sulfur. The energy from this reaction is then used to reduce carbon dioxide to create carbohydrates. An example of a colorless sulfur bacteria is the genus *Thiothrix.*

Another type of chemoautotroph is the "iron" bacteria. These bacteria are most commonly encountered as the rusty colored and slimy layer that builds up on the inside of toilet tanks. In a series of chemical reactions that is similar to those of the sulfur bacteria, iron bacteria oxidize iron compounds and use the energy gained from this reaction to drive the formation of carbohydrates. Examples of iron bacteria are *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans*. These bacteria are common in the **runoff** from **coal** mines. The water is very acidic and contains ferrous iron. Chemoautotrophs thrive in such an environment.

A third type of chemoautotrophic bacteria includes the nitrifying bacteria. These chemoautotrophs oxidize ammonia (NH_3) to nitrate (NO_3^-). Plants can use the nitrate as a nutrient source. These nitrifying bacteria are important in the operation of the global nitrogen cycle. Examples of chemoautotrophic nitrifying bacteria include Nitrosomonas and Nitrobacter.

The **evolution** of bacteria to exist as chemoautotrophs or chemolithotrophs has allowed them to occupy niches that would otherwise be devoid of bacterial life. For example, in recent years scientists have studied a **cave** near Lovell, Wyoming. The **groundwater** running through the cave contains a strong sulfuric acid. Moreover, there is no sunlight. The only source of life for the thriving bacterial populations that adhere to the rocks are the rocks and the **chemistry** of the groundwater.

The energy yield from the use of inorganic compounds is not nearly as great as the energy that can be obtained by other types of bacteria. Regardless, chemoautotrophs and chemolithotrophs do not usually face competition from other microorganisms, so the energy they are able to obtain is sufficient to sustain their existence.

The ability of chemoautotrophic and chemolithotrophic bacteria to thrive through the energy gained by inorganic processes is the basis for the metabolic activities of the so-called extremophiles. These are bacteria that live in extremes of **pH**, **temperature**, or pressure, as three examples. Moreover, it has been suggested that the metabolic capabilities of extremophiles could be duplicated on extraterrestrial planetary bodies.

See also Erosion; Geochemistry; Weathering and weathering series

CHERT

Chert, or cryptocrystalline **quartz**, is a microcrystalline variety of the mineral quartz (SiO_2) that is chemically or biochemically precipitated from seawater. Chert is just one of the many types, or polymorphs, of quartz, a mineral composed of three-dimensionally bonded silicate tetrahedra. Chert is very fine-grained, so it does not occur as the 6-sided, prismatic **crystals** typical of such coarsely crystalline varieties of quartz as **rock** crystal, amethyst, smoky quartz and citrine. It does, however, have the mineral properties of quartz. It has a glassy, or vitreous, luster, it is number seven on the Moh's scale of hardness, and it breaks along uneven, shell-shaped planes, a property called conchoidal fracture. Other microcrystalline varieties of quartz include chalcedony, agate, onyx and jasper. Dark grey, unbanded chert is better known as flint. Early hunters and warriors exploited chert's characteristic hardness and conchoidal fracture to create sharp-edged, durable tools and weapons; they also discovered that the hard, smooth surface of a flint nodule or shard can be used to strike a spark.

Silica is mainly extracted from seawater by the biochemical actions of marine organisms. Microscopic aquatic plants, called **diatoms**, take in silicate (SiO_4^{4-}) ions from seawater and use them to create siliceous hard parts, or frustules. When the plants die, the frustules fall to the seafloor, creating layers of uncrystallized siliceous "ooze." Compaction and cementation of these layers of silica creates chert. Opal is solid marine silica that has not yet bonded into a rigid crystal framework. Chert usually occurs as bands or nodules in **limestone**, a marine sedimentary rock that forms by the same mechanism of biological mineral **precipitation**. Organisms like corals and foraminifera, which contribute their hard parts to limestone use calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions to create their skeletons and shells. Limestone, accordingly, is composed of the mineral calcite ($CaCO_3$) instead of quartz, but like chert, it is a geological remnant of a biologically productive marine environment.

See also Calcareous Ooze; Sedimentary Rocks

CHICXULUB CRATER • *see* K-T EVENT

CHINOOK WINDS • *see* SEASONAL WINDS

CHLOROFLUOROCARBON (CFC)

A chlorofluorocarbon (CFC) is an organic compound typically consisting of chlorine, fluorine, **carbon**, and hydrogen. Freon, a trade name, is often used to refer to CFCs, which were invented in the 1930s and have been used widely as aerosol propellants, refrigerants, and solvents. Odorless, colorless, nontoxic, and nonflammable, CFCs are considered valuable industrial products and have proven an especially safe and reliable aid in food preservation. However, the accumulation of CFCs in the **stratosphere** that may be linked to **ozone** depletion has generated considerable public debate and has led to legislation and international agreements (such as the Montreal Protocol and its amendments, signed by 148 countries) that banned the production of most CFCs by the year 2000. One of the substitutes developed by industry, the hydrochlorofluorocarbons (HCFCs), still contain enough chlorine to interfere with atmospheric ozone **chemistry**, although in much lesser amounts than CFCs. The Copenhagen amendment to the Montreal Protocol calls for the cessation of HCFC production by 2030. Hydrofluorocarbons (HFCs) are currently considered a safer substitute due to prevent ozone loss due to their lack of chlorine and shorter reactive time. As of 2002, new automobiles in the United States contain HFC refrigerant products in the air conditioners.

In the late 1920s, researchers had been trying to develop a coolant that was both nontoxic and nonflammable. At that time, methyl chloride was used, but if it leaked from the refrigerator, it could explode. This danger was demonstrated in one case when methyl chloride gas escaped, causing a disastrous explosion in a Cleveland hospital. Sulfur dioxide was sometimes used as an alternative coolant because its unpleasant odor could be easily noticed in the event of a leak. The problem was brought to the attention of Thomas Midgley Jr., a mechanical engineer at the research laboratory of General Motors. He was asked by his superiors to try to manufacture a safe, workable coolant. (At that time, General Motors was the parent company to Frigidaire.) Midgley and his associate chemists thought that fluorine might work because they had read that carbon tetrafluoride had a boiling point of 5°F (–15°C). The compound, as it turns out, had accidentally been referenced. Its actual boiling point is 198°F (92.2°C), not nearly the level necessary to produce refrigeration. Nevertheless, the incident proved useful because it prompted Midgley to look at other carbon compounds containing both fluorine and chlorine. Within three days, Midgley's team discovered the right mix: dichlorodifluoromethane, a compound whose molecules contain one carbon, two chlorine, and two fluorine atoms. It is now referred to as CFC-12 or F-12 and was marketed as Freon—as were a number of other compounds, including trichlorofluoromethane, dichlorotetrafluoroethane, and chlorodifluoromethane.

Midgley and his colleagues had been correct in guessing that CFCs would have the desired thermal properties and boiling points to serve as refrigerant gases. Because they remained unreactive, and therefore safe, CFCs were seen as ideal for many applications. Through the 1960s, the widespread manufacture of CFCs allowed for accelerated production of refrigerators and air conditioners. Other applications for CFCs were discovered as well, including their use as blowing agents in polystyrene foam. Despite their popularity, CFCs became the target of growing environmental concern by certain groups of researchers. In 1972, two scientists from the University of California, **F. Sherwood Rowland** and Mario Jose Molino, conducted tests to determine if the persistent characteristics of CFCs could pose a problem by remaining indefinitely in the atmosphere. Soon after, their tests confirmed that CFCs do indeed persist until they gradually ascend into the stratosphere, break down due to ultraviolet radiation, and release chlorine, which in turn affects ozone production. Their discovery set the stage for vehement public debate about the continued use of CFCs. By the mid-1970s, the United States government banned the use of CFCs as aerosol propellants but it resisted a total ban for all industries. Instead, countries and industries began negotiating the process of phasing out CFCs. As CFC use is allowed in fewer and fewer applications, a black market has been growing for the chemical. In 1997, the United States Environmental Protection Agency and Customs Service, along with other governmental agencies, initiated enforcement actions to prevent (CFC) smuggling in the United States.

See also Atmospheric pollution; Global warming; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ozone layer depletion

CHRONOSTRATIGRAPHY

The term chronostratigraphy refers to that aspect of the field of **stratigraphy** dealing with temporal (time) relations and ages of **rock** bodies. Chronostratigraphic classification in the field of stratigraphy organizes rocks on the basis of their age or the time of their genesis.

Chronostratigraphic units are defined as bodies of rock—stratified and non-stratified—that formed during a specific interval of **geologic time**. Chronostratigraphic units are thus special rock bodies that are conceptual, as well as being material. They can be thought of as the subset of rocks formed during a specified geologic time interval.

For example, the Devonian System is the set of all rocks (sedimentary as well as igneous and metamorphic), wherever they occur on Earth, formed during the **Devonian Period**. The boundaries of this conceptual set of rocks are synchronous (i.e., are the same age everywhere) and the Devonian System is isochronous (i.e., the same age and age span everywhere). When written with a proper noun, e.g., Devonian System, both parts of the name of any chronostratigraphic unit are capitalized.

Chronostratigraphic units, like the system, are the basis for the Phanerozoic time scale. Chronostratigraphic units have a hierarchy, wherein there are corresponding geochronologic units. The chronostratigraphic hierarchy (with corresponding geochronologic term and example proper name) is as follows:

- Erathem—Corresponding geochronologic term: Eon; Example: Phanerozoic
- Eonothem—Corresponding geochronologic term: Era; Example: Paleozoic
- System—Corresponding geochronologic term: Period; Example: Devonian
- Series—Corresponding geochronologic term: Epoch; Example: Late Devonian
- Stage—Corresponding geochronologic term: Age; Example: Frasnian
- Substage—Corresponding geochronologic term: Subage

Because chronostratigraphic units are potentially vast vertical section of rock, geologists observe the following conventions with regard to reference markers placed at agreed sites, which represent the best reference examples of the lower boundaries of chronostratigraphic units. These sites, called Global Stratotype Sections and Points (GSSPs), help define chronostratigraphic units. Not all the necessary GSSPs have been assigned yet, and the work continues under the auspices of the International Union of Geological Sciences (IUGS).

The system is the fundamental chronostratigraphic unit, meaning that it is the most commonly used and referenced chronostratigraphic unit. Further, the system was the original unit conceived of in early chronostratigraphic classification. The system is a major subdivision within the hierarchy of chronostratigraphic units, and the largest system spans approximately 152 million years of Earth history. However, most systems span fewer years. Some systems are subdivided into two subsystems (i.e., Tertiary System is subdivided into Neogene and Paleogene Subsystems and Carboniferous System is subdivided into Pennsylvanian and Mississippian Subsystems). A list of the main Phanerozoic systems (with approximate age ranges in millions of years) are: Quaternary (0 to 1.64 millions of years); Tertiary (1.64 to 65 millions of years); Cretaceous (65 to 145.8 millions of years); Jurassic (145.8 to 208 millions of years); Triassic (208 to 245 millions of years); Permian (245 to 290 millions of years); Carboniferous (290 to 362.5 millions of years); Devonian (362.5 to 408.5 millions of years); Silurian (408.5 to 439 millions of years);Ordovician (439 to 505 millions of years); Cambrian (505 to 570 millions of years).

The boundary ages are determined by radiometric age-bracketing and biostratigraphic relationships.

Names of systems are of diverse origin arising from workers of the eighteenth and nineteenth centuries. System names indicate either (1) chronostratigraphic position (e.g., Tertiary and Quaternary), (2) geologic characteristics, e.g., Carboniferous and Cretaceous (*Creta* is Latin for “chalk”), (3) geographic locations, e.g., Devonian and Permian (named for the Perm Province of Czarist Russi), and (4) native people’s tribal names, e.g., Ordovician and Silurian (named for Celtic tribes of southern England). Proper names of systems have no common spelling for their endings, despite some attempts in the past to standardize them. Systems and corresponding periods have the same proper name.

Names of relatively new and all future series, stages, and substages come from local geographic features in the vicinity of their designated stratotype (i.e., the place where the unit is defined for reference purposes) or their GSSP (i.e., the place where the base of the unit is defined for reference purposes). However, some older names (pre-1970s) have come from other sources before the geographic convention was established. Within some systems, names of series are formed from the system plus a positional adjective (lower, middle, or upper). Most names have an “-ian” or “-an” ending. Epochs, ages, and subages have the same name as the corresponding chronostratigraphic unit (i.e., series, stage, and substage). The only exception is where a series bears a positional adjective. In these instances, the positional adjective for the series is replaced by a temporal adjective to form the corresponding epoch. For example, the Lower Devonian Series was formed during the Early Devonian Epoch, Middle Devonian Series was formed during the Middle Devonian Epoch, and Upper Devonian Series was formed during the Late Devonian Epoch.

Names of Erathems and Eonothems reflect major changes in existing life on Earth. Regarding the Erathems, Paleozoic means “old life,” Mesozoic means “middle life,”’ and Cenozoic means “recent life.” For Eonothems, Phanerozoic (which encompasses Paleozoic, Mesozoic, and Cenozoic) means “evident life.” Older Eonothems are Hadean (in reference to the fiery beginning of Earth), **Archean** (in reference to ancient times), and Proterozoic (in reference to primitive life). Erathems and Eonothems (with their corresponding approximate ages in millions of years) age span chronostratigraphic units; Phanerozoic—Cenozoic (0 to 65 millions of years), Mesozoic (65to 245 millions of years), and Paleozoic (245 to 570 millions of years)—Proterozoic (570 to 2450 millions of years); Archean (2450 to 3800 millions of years) and Hadean (3800 to 4560 millions of years).

See also Dating methods; Phanerozoic Eon; Stratigraphy

CIRQUE • *see* ARETES

CIRRIFORM • *see* CLOUDS AND CLOUD TYPES

CIRROCUMULOUS • *see* CLOUDS AND CLOUD TYPES

CIRRUS • *see* CLOUDS AND CLOUD TYPES

CLAY

Clay is a fine-grained (small particle size) sedimentary **rock**. Clay is so fine-grained it is rarely possible to see the individual mineral particles with the naked eye. The definition of clays describes rocks with particle sizes of less than 4 µm in diameter. Most **sedimentary rocks** are described using both mineral content and particle size. While this is also true for clays, the particle size description is most reliable and most often used.

The majority of common types of **minerals** found in clays are kaolinite (a soapy-feeling and lightweight mineral), talc, pyrophyllite, all types of micas, minerals from the chlorite group, feldspars, and a lesser amount of **tectosilicates** (including **quartz**).

The mineral content of clays is less variable than other types of sedimentary rock. This is a direct result of the way clays are formed. **Water** carries the bulk of sediments to their resting place where they are cemented together. The transport of sediments is directly related to the force or velocity of water carrying them. The stronger the velocity of water, the larger and heavier the particle it can move. Conversely, the weaker the flow, the smaller the particle that is carried by the water. As a result, water acts as a winnowing filter for certain types of minerals. The heavier minerals are not carried as far by water currents as are the lighter ones. When water finally comes to rest, it deposits its load of minerals. The last to be released are the lighter and smaller particles, the clay minerals.

Where **rivers** meet **oceans**, the clay minerals are so light they are usually carried far out to sea where they fall gently to the bottom forming a fine-grained sediment. These deposits cover organic materials and trap them at the edges of deltas and continental slopes. Over millions of years, the organic materials convert to **petroleum** and remain trapped by the clays. This relationship makes the study of clays extremely important for petroleum geologists. In addition to this important economic consideration, clays provide important economic resources for a wide variety of other industries.

See also Petroleum detection; Sedimentation

CLIMATE • *see* WEATHER AND CLIMATE

CLOUD SEEDING

Mark Twain once said that everyone talks about the **weather**, but no one ever does anything about it. Although he may have been correct in his day, since the 1940s, researchers have been at least partially successful in modifying one aspect of the weather—precipitation.

After about three years of investigative work at the General Electric Research Laboratory in Schenectady, New York, researchers Irving Langmuir and his assistant, Vincent Joseph Schaefer, created the first human-made rainfall. Their work had originated as war-influenced research on airplane wing icing. On November 13, 1946, Schaefer sprinkled several pounds of dry **ice** (frozen **carbon dioxide**) from an airplane into a supercooled cloud, a cloud in which the **water** droplets remain liquid in sub-zero temperatures. He then flew under the cloud to experience a self-induced snowfall. The snow changed to rain by the time it reached Langmuir, who was observing the experiment on the ground.

Langmuir and Schaefer selected dry ice as cloud "seed" for its quick cooling ability. As the dry ice travels through the cloud, the water vapor behind it condenses into rain-producing **crystals**. As the crystals gain weight, they begin to fall and grow larger as they collide with other droplets.

Another General Electric (GE) scientist who had worked with Langmuir and Schaefer, Bernard Vonnegut, developed a different cloud-seeding strategy. The formation of water droplets requires microscopic nuclei. Under natural conditions, these nuclei can consist of dust, smoke, or sea salt particles. Instead of using dry ice as a catalyst, Vonnegut decided to use substitute nuclei around which the water droplets in the cloud could condense. He chose silver iodide as this substitute because the shape of its crystals resembled the shape of the ice crystals he was attempting to create.

The silver iodide was not only successful, it had practical advantages over dry ice. It could be distributed from the ground through the use of cannons, smoke generators, and natural cumulonimbus cloud updrafts. Also, it could be stored indefinitely at room **temperature**.

There is general disagreement over the success and practicality of cloud seeding. Opponents of cloud seeding contend that there is no real proof that the **precipitation** experienced by the seeders is actually of their own making. Proponents, on the other hand, declare that the effect of seeding may be more than local.

Over the years, cloud seeding has become an accepted part of the strategy to combat **drought**. It may indeed bring crop-saving relief to a dry field or may help reinforce subsurface water tables. However, the practice has not begun to eliminate deserts or devastating droughts, for researchers have yet to reproduce the general ground-soaking effects of a well-organized natural storm system so necessary for agriculture and replenishment of water reserves. And today there are environmental concerns over any activity that threatens to change or destroy a bio-community such as the **desert**.

As researchers collect and analyze more information about the weather, other attempts to modify it are bound to be developed.

See also Air masses and fronts; Weather forecasting; Weather forecasting methods

CLOUDS AND CLOUD TYPES

Clouds are condensations of **water** and other particles in the atmosphere. Cloud shapes—and the dynamics of their formation—are accurate indicators of important atmospheric properties, including air stability, moisture content, and motion.

Clouds are divided into families of high level, middle level, low level, and vertically developing clouds, and are classified again, in accord with their general shape (e.g., cumuliform or stratoform)

High level clouds include cirrus, cirrostratus, and cirrocumulus clouds that occur at altitudes between 16,000 and 45,000 feet. Middle level clouds include altostratus, altocumulus, and nimbostratus clouds that occur between 6500 and 22,000 feet. Low-level clouds include stratus and stratocumulus clouds that occur between the surface and 6,500 feet. Vertical development clouds include cumulus and cumulonimbus clouds, and range in their development from the surface to 45,000 feet. The heights of the bases of the clouds used to designate cloud families can vary with **latitude**. At extreme northern or southern latitudes, high altitude family clouds can be observed at much lower altitudes.

In general, cloud shape is determined by the method of cooling to reach **condensation** and the forces of winds that can shear or tear the cloud. Cloud opacity (i.e., whether it is light or dark) is a function of cloud thickness.

Cirrus clouds occur at high levels and are generally wispy and elongate in form. Vertically rising air is unstable and gives rise to cumulus cloud formation. Cumulus clouds are billowy. Stratus clouds (i.e., stratified clouds) are heavily layered and often appear in sheet-like formations. With regard to cloud nomenclature, nimbus clouds (e.g., clouds with the prefix nimbo or the suffix nimbus) are rain-producing clouds. The use of "fracto" designates broken cloud formations.

High clouds—cirrus, cirrostratus, and cirrocumulus—are composed of **ice crystals** and dust or pollution particles. The particles often serve as centers of crystallization or condensation nuclei. Cirrus clouds often produce "mares' tails" that are tail-like wisps of ice crystals. Cirrostratus clouds, because they are thin and the ice crystals act to both reflect and refract sunlight, are often associated with halos of ice crystals that appear to encircle the **Sun** or **Moon**. Cirrocumulus clouds often appear as patch-like thin clouds.

Middle level cloudsmdash; altostratus, altocumulus, and nimbostratus—are composed of water with some ice crystal formation near cloud tops. Both middle level and low level clouds may be composed of super-cooled water (water below **freezing**) that has not yet crystallized around a condensation nucleus. Altostratus clouds often present a bluish-layered appearance. Depending on thickness, altocumulus clouds often have white or gray layers that appear in washboard or wave-like formations. Atmospheric instability and convective air currents can result in the formation of altocumulus castellanus clouds, a form of altocumulus that often appear as isolated cumulous clouds with billowing tops. Another form of altocumulus cloud, a standing lenticular altocumulus clouds, is formed by turbulent updrafts of air uplifted by terrain barriers (e.g., mountains, ridges, etc.). Although dynamic, the standing lenticular altocumulus cloud formations appear static or "standing" over the terrain feature leading to their formation. Nimbostratus clouds often appear as heavy, gray, moisture-laden cloud layers

Low-level stratus clouds are usually gray clouds associated with **precipitation** and **fog**. Stratocumulus clouds present the familiar, cotton ball-like cumulus shapes in an elongate form (a cumulus shape drawn out by shearing winds).

Clouds with extensive vertical development—cumulus and cumulonimbus clouds—often present a gradient of ice and water. Rapid updrafts and downdrafts allow ice crystals to appear at much lower levels than would be expected by atmospheric **temperature**. Although arising from convective currents, cumulus clouds often form in fair **weather** and do not show extensive vertical development. Cumulus clouds present flat bases and curved or domed tops. More extensive vertical development occurs as atmospheric instability increases. Highly developed cumulus clouds often present mushroomed or cauliflower-like tops, and can ultimately produce rain. Under the most unstable of atmospheric conditions, cumulonimbus clouds form. Cumulonimbus clouds are dark clouds with anvil like tops sheared by very high altitude winds. Heavy turbulence, violent rains, **lightning**, and **thunder** often accompany cumulonimbus clouds. Particularly unstable and violent clouds can occur in cells capable of spawning tornadoes.

The identification of cloud types is an important skill for aviators and aviation meteorologists because clouds present variable icing hazards. Ice formation can drastically reduce the effectiveness of airfoils (wings, flaps, rudder, ailerons, elevators) and destroy lift and/or interfere with the ability to control aircraft.

See also Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pressure; Phase state changes; Troposphere and tropopause; Weather forecasting methods; Weather forecasting; Weather radar; Wind shear

COAL

Coal is a naturally occurring combustible material consisting primarily of the element **carbon**, but with low percentages of solid, liquid, and gaseous **hydrocarbons** and other materials, such as compounds of nitrogen and sulfur. Coal is usually classified into the sub-groups known as anthracite, bituminous, lignite, and peat. The physical, chemical, and other properties of coal vary considerably from sample to sample.

Coal forms primarily from ancient plant material that accumulated in surface environments where the complete decay of organic matter was prevented. For example, a plant that died in a swampy **area** would quickly be covered with **water**, silt, **sand**, and other sediments. These materials prevented the plant debris from reacting with **oxygen** and decomposing to **carbon dioxide** and water, as would occur under normal circumstances. Instead, anaerobic bacteria (bacteria that do not require oxygen to live) attacked the plant debris and converted it to simpler forms: primarily pure carbon and simple compounds of carbon and hydrogen (hydrocarbons). Because of the way it is formed, coal (along with **petroleum** and **natural gas**) is often referred to as a fossil fuel.

The initial stage of the decay of a dead plant is a soft, woody material known as peat. In some parts of the world, peat is still collected from boggy areas and used as a fuel. It is not a good fuel, however, as it burns poorly and with a great deal of smoke.

If peat is allowed to remain in the ground for long periods of time, it eventually becomes compacted as layers of sediment, known as overburden, collect above it. The additional pressure and heat of the overburden gradually converts peat into another form of coal known as lignite or brown coal. Continued compaction by overburden then converts lignite into bituminous (or soft) coal and finally, anthracite (or hard) coal. Coal has been formed at many times in the past, but most abundantly during the Carboniferous Age (about 300 million years ago) and again during the Upper Cretaceous Age (about 100 million years ago).

Today, coal formed by these processes is often found in layers between layers of sedimentary **rock**. In some cases, the coal layers may lie at or very near the earth's surface. In other cases, they may be buried thousands of feet or meters under ground. Coal seams range from no more than 3–197 ft (1–60 m) or more in thickness. The location and configuration of a coal seam determines the method by which the coal will be mined.

Coal is classified according to its heating value and according to its relative content of elemental carbon. For example, anthracite contains the highest proportion of pure carbon (about 86%–98%), and has the highest heat value (13,500–15,600 Btu/lb [British thermal units per pound]) of all forms of coal. Bituminous coal generally has lower concentrations of pure carbon (from 46%–86%) and lower heat values (8,300–15,600 Btu/lb). Bituminous coals are often sub-divided on the basis of their heat value, and are classified as low, medium, and high volatile bituminous and sub-bituminous. Lignite, the poorest of the true coals in terms of heat value (5,500–8,300 Btu/lb) generally contains about 46%–60% pure carbon. All forms of coal also contain other elements present in living organisms, such as sulfur and nitrogen, that are very low in absolute numbers, but that have important environmental consequences when coals are used as **fuels**.

By far the most important property of coal is that it combusts. When the pure carbon and hydrocarbons found in coal burn completely, only two products are formed, carbon dioxide and water. During this chemical reaction, a relatively large amount of energy is released. The release of heat when coal is burned explains the fact that the material has long been used by humans as a source of energy, for the heating of homes and other buildings, to run ships and trains, and in many industrial processes.

The complete combustion of carbon and hydrocarbons described above rarely occurs in nature. If the **temperature** is not high enough or sufficient oxygen is not provided to the fuel, combustion of these materials is usually incomplete. During the incomplete combustion of carbon and hydrocarbons, other products besides carbon dioxide and water are formed, primarily carbon monoxide, hydrogen, and other forms of pure carbon, such as soot.

During the combustion of coal, minor constituents are also oxidized. Sulfur is converted to sulfur dioxide and sulfur trioxide, and nitrogen compounds are converted to nitrogen oxides. The incomplete combustion of coal and the combustion of these minor constituents result in a number of environmental problems. For example, soot formed during incomplete combustion may settle out of the air and deposit an unattractive coating on homes, cars, buildings, and other structures. Carbon monoxide formed during incomplete combustion is a toxic gas and may cause illness or death in humans and other animals. Oxides of sulfur and nitrogen react with water vapor in the atmosphere and then are precipitated out as **acid rain**. Acid rain is thought to be responsible for the destruction of certain forms of plant and animal (especially fish) life.

In addition to these compounds, coal often contains a few percent of mineral matter: **quartz**, calcite, or perhaps **clay minerals**. These do not readily combust and so become parts of the ash. The ash then either escapes into the atmosphere or is left in the combustion vessel and must be discarded. Sometimes coal ash also contains significant amounts of **lead**, barium, arsenic, or other compounds. Whether air borne or in bulk, coal ash can therefore be a serious environmental hazard.

Coal is extracted using one of two major techniques, sub-surface or surface (strip) mining. The former method is used when seams of coal are located at significant depths below Earth's surface. The first step in sub-surface mining is to dig vertical tunnels into the earth until the coal seam is reached. Horizontal tunnels are then constructed laterally off the vertical tunnel. In many cases, the preferred method of mining coal by this method is called room-and-pillar mining. In this method, vertical columns of coal (the pillars) are left in place as coal around them is removed. The pillars hold up the ceiling of the seam, preventing it from collapsing on miners working around them. After the mine has been abandoned, however, those pillars may often collapse, bringing down the ceiling of the seam and causing subsidence in land above the old mine.

Surface mining can be used when a coal seam is close enough to the earth's surface to allow the overburden to be removed economically. In such a case, the first step is to strip off all of the overburden in order to reach the coal itself. The coal is then scraped out by huge power shovels, some capable of removing up to 100 cubic meters at a time. Strip mining is a far safer form of coal mining, but it presents a number of environmental problems. In most instances, an area that has been strip-mined is scarred, and restoring the area to its original state is a long and expensive procedure. In addition, any water that comes in contact with the exposed coal or overburden may become polluted and require treatment.

Coal is regarded as a non-renewable resource, meaning that it was formed at times during Earth's history, but significant amounts are no longer forming. Therefore, the amount of coal that now exists below the earth's surface is, for all practical purposes, all the coal that humans have available to them for the foreseeable future. When this supply of coal is used up, humans will find it necessary to find some other substitute to meet their energy needs.

Large supplies of coal are known to exist (proven reserves) or thought to be available (estimated resources) in **North America**, the former Soviet Union, and parts of **Asia**, especially China and India. According to the most recent data available, China produces the largest amount of coal each year, about 22% of the world's total. China is also thought to have the world's largest estimated resources of coal, as much as 46% of all that exists.

For many centuries, coal was burned in small stoves to produce heat in homes and factories. Today, the most important use of coal, both directly and indirectly, is still as a fuel. The largest single consumer of coal as a fuel is the electrical power industry. The combustion of coal in power generating plants is used to make steam, which in turn, operates turbines and generators. For a period of more than 40 years, beginning in 1940, the amount of coal used in the United States for this purpose doubled in every decade. Coal is no longer widely used to heat homes and buildings, as was the case a half century ago, but it is still used in industries such as paper production, cement and ceramic manufacture, **iron** and steel production, and chemical manufacture for heating and for steam generation.

See also Environmental pollution

COBBLE • *see* ROCK

COCCOLITHOPHORIDS • *see* CALCAREOUS OOZE

COMETS

Comets are objects—relatively small compared to planets—that are composed of dust and ices of various compounds. Comets orbit the **Sun** in elongated elliptical (eccentric, elongated circle) or parabolic orbits. Accordingly, these objects spend the majority of time in the outer regions of the **solar system**, in some cases well beyond the orbits of Neptune and Pluto. Short-period comets are those with less exaggerated elliptical orbits that carry them out only as far as the region of **space** between the orbits of Jupiter and Neptune. Comets make periodic, brief, but sometimes-spectacular transits through the inner solar system as they approach the Sun. Comet orbits may be prograde, in the same direction as the planets, or retrograde, in the opposite direction. With the aid of a **telescope**, a comet is usually visible from Earth.

The term "comet" derives from the Greek *aster kmetes* (translated literally as "hairy" or long-haired star)—a reference to a sometimes-visible comet tail. If a comet's path takes it close enough to the Sun, the heating causes **melting** and emission of gases (out gassing) and dust that are then swept behind the comet's orbital path (away from the Sun) by the solar **wind** to form the characteristic tail.

Fascination with objects in the night sky dates to the dawn of human civilization. Etchings on **clay** tablets unearthed in the ancient city of Babylon dating to at least 3000 B.C. and **rock** carvings found in prehistoric sites in Scotland dating to 2000 B.C. depict unexplained astronomical phenomena that may have been comets. Until the Arabic astronomers of the eleventh century, the Chinese were by far the most astute skywatchers in the ancient and medieval world. By 400 B.C., their intricate cometary classification system included sketches of

29 comet forms, each associated with a past event and predicting a future one. Comet type 9 was named Pu-Hui, meaning "Calamity in the state, many deaths." In fact, until the seventeenth century when English Astronomer Edmund Halley (1656–1742) predicted the return of a the comet in 1758 (thereafter known as Halley's comet) based, in part, upon calculations derived from English physicist and mathematician Sir Isaac Newton's (1642–1727) work, comets were widely viewed with superstition, as omens portending human disasters and terrestrial catastrophes.

Recorded observation of comets is evident in the records of the Ancient Chinese culture who termed comets "guest stars," a general term also applied to other apparent temporary solar system transients that were later, of course, identified to be much more distant stellar novae. Chinese records clearly indicate the transit of a guest star in approximately 240 B.C. that we now identify as Halley's comet.

In accord with Anasazi Native American accounts, Chinese astronomers also noted the difference in what is now regarded as comets and the 1054 supernova explosion in the Taurus constellation (i.e., a region of the sky associated with the Taurus constellation) that created the Crab Nebula.

Of all the Classical Greek and Roman theories on comets, the most influential, though entirely incorrect, was that of the Greek philosopher Aristotle (384–322 B.C.). His geocentric view of the solar system put Earth at the center circled by the Sun, **Moon**, and visible planets. Stars were stationary and the bodies existed on celestial spheres. Aristotle argued that comets were fires in the dry, sublunar "fiery sphere," a combustible atmosphere "exhaled" from Earth, which accumulated between Earth and the Moon. Comets were therefore considered terrestrial—originating from Earth, rather than celestial—heavenly bodies. Moreover, they were seen as a portent of future events controlled by the gods.

Aristotle's writings formed the basis of later Greek-Alexandrian astronomer Ptolemy's (A.D. 87–150) model of the universe that became strongly supported by the Christian church in Western **Europe**. Because the Ptolemy's model provided accurate results with regard to celestial prediction, it was the most influential astronomical model until the acceptance of the Sun-centered (heliocentric) model put forth by Polish astronomer Nicolaus Copernicus (1473–1543).

In conjunction with the German astronomer and mathematician **Johannes Kepler** (1571–1630), Danish astronomer Tycho Brahe's (1546–1601) observation of the "Great Comet" of 1577 provided evidence that the comet was at least four times further away from Earth than the Moon—a crushing refutation of Aristotle's sublunar positioning.

The study of the Great Comet by Brahe and his contemporaries was the turning point for astronomical science. Throughout the seventeenth and eighteenth centuries, mathematicians and astronomers refined conflicting ideas on the origin, formation, movement, shape of orbit, and meaning of comets. Polish-born scientist Johannes Hevelius (1611–1687), who suggested comets move on a parabola (U-shape) around the Sun; and English scientist Robert Hooke (1635–1703), independent of Newton, introduced the theory of universal gravitational influence based, in part on the periodic behavior of comets. Newton, however, developed an astounding mathematical model for the parabolic motion of comets, published in his seminal and influential 1687 book, *Philosophiae Naturalis Principia Mathematica* (Mathematical principles of natural philosophy). Until English naturalist Charles Darwin's (1809–1882) writings on **evolution** and German-American physicist Albert Einstein's (1879–1955) twentieth century writings on **relativity theory**, *Principia* remained the single most influential scientific work in the history of science."

By the end of the eighteenth century, comets were understood to be astronomical bodies, the movement of which could be calculated using Newton's laws of planetary motion.

The comet Biela, with a periodic orbit of 6.75 years, split in two during its 1846 appearance. Twin comets reappeared in 1852—but then failed to appear for its next pass. The disappearance fostered scientific speculation regarding comet impacts and their relationships to meteor showers. When Biela's twin offspring should have returned, the meteor shower predicted by some astronomers did indeed appear, strengthening the connection between meteors and dying comets.

The first observation of a comet through a telescope was made in 1618. Until the twentieth century, comets were discovered and observed with the naked eye or through telescopes. Today, most new discoveries are made from photographs of our galaxy and electronic detectors, although many discoveries are still made by amateur astronomers with a passion for careful observation.

The long focal-length refracting telescope, the primary astronomical observation tool of the 1800s, worked well for viewing bright objects but did not collect sufficient light to allow detailed astronomical photography. In 1858, an English artist named Usherwood used a short focal-length lens to produce the first photograph of a comet. In 1864, by using a spectroscope, an instrument that separates the wavelengths of light into spectral bands, Italian astronomer Giovanni Donati (1826–1873) first identified a chemical component in a comet's atmosphere. The first cometary spectrogram (spectral photograph) was taken by amateur astronomer William Huggins of London in 1881.

The early twentieth century saw the development of short focal-length spectrographs that, by the 1950s, allowed identification of several different chemical components in a comet's tail. Infrared spectrography was introduced in the 1960s and, in 1983, the Infrared Astronomy Satellite (IRAS) gathered information on cometary dust particles unattainable from ground-based technology. Observations of comets are now also made by radio wave detection and ultraviolet spectrography.

Spectroscopic evidence indicates that most comets contain a solid nucleus (core) surrounded by a gigantic, glowing mass (coma). Together, the nucleus and coma comprise the comet head. It should be noted that although the tail (when apparent) seems dense with dust and gas, it is still a vacuum that is far less dense than the interplanetary space near the earth (e.g., between the earth and Moon).

Perhaps among the most primitive bodies in the solar system, comets are probably debris from the formation of our Sun and planets some 4.5 billion years ago. One hypothesis

Comet Hale-Bopp. ***Jack Newton. Archive Photos, Inc. Reproduced by permission.***

concerning their origin involves the Oort cloud—named for Dutch astronomer Jan Van Oort—a dense shell of debris (dense by interstellar standards) at the frigid, outer edge of the solar system (i.e., the distance at which our Sun's gravitational pull is so weak that beyond this point other stellar bodies exert a greater net attraction). Occasionally, disruptive gravitational forces (perturbations) hurl a piece of debris from the cloud into the gravitational pull of one of the large planets, (e.g. Jupiter or Saturn) that then pull the comet into an elliptical orbit around the Sun. The Kuiper belt, associated with Jupiter's gravitational pull, is more likely the source of the well-known comets, including Halley's comet. Regardless, evidence indicates that comets formed from solar system formation debris.

Short lived comets have orbital durations of less than 200 years. Long-period, having enormous elliptical, nearly parabolic orbital durations of more than 200 years, often traveling far beyond the outer planets. Of the 710 individual comets recorded from 1680 to mid-1992, 121 were short-period comets and 589 were classified as long-period comets.

Two major theories on the composition of the nucleus have developed over time. The "flying sandbank" model, first proposed by Richard Proctor in the mid-1800s and again in the mid-1900s by Raymond Lyttleton, conjectured swarms of tiny solid particles bound together by mutual gravitational attraction. In 1950, Fred Whipple introduced the "icy-conglomerate" model, which described a comet as a solid nucleus of meteoric rock particles and dust frozen in **ice**. Observations of Halley's comet by spacecraft in 1986 strongly support this model.

Evidence to date indicates that within the comet head or nucleus, rocks and dust are held together with ices from **water**, methane, ammonia, and **carbon** monoxide, as well as other ices containing carbon and sulphur. The 1986 studies of Halley's comet revealed the nucleus to be peanut or potato-shaped, 9 mi (15 km) long, and 5.5 mi (8 km) wide. However, visual observation beneath the comet's dark, solid surface proved impossible.

The nuclei of comets are among the smallest bodies in the Solar system, too small, in fact, for observation even through a telescope. As they approach the Sun, however, they produce one of the largest, most spectacular sights in the solar system, a magnificent, glowing coma often visible even to the naked eye. Comet nuclei have been seen to produce sudden, bright flares and some even split into two, three, four, or five refions.

As the nucleus of a comet approaches the Sun, beginning at about the distance of the asteroid belt, its ices begin to vaporize and sublimate (change directly from ice to gas). This off-gassing releases gases of hydrogen, carbon, **oxygen**, nitrogen and other molecules, as well as dust particles. Streaming away at several hundred meters per second, they create an enormous coma hundreds of thousands of kilometers long, completely hiding the nucleus. The Sun's ultraviolet light electrically charges the gaseous molecules, ionizing and exciting them, causing them to fluoresce (emit light) much like a fluorescent light emits light following electrical stimulation. Microscopic mineral particles in the dust reflect and scatter the Sun's light. Only in 1970, during the first spacecraft observation of a comet, was a gigantic hydrogen cloud discovered surrounding the Coma. Depending on the size of the nucleus and its proximity to the Sun, this cloud can be much larger than the comet itself.

As the comet swings around the Sun on its elliptical orbit, gas and dust particles stream from the coma to create two types of tails: the gaseous ion tail, or Type I; and the dust tail, or Type II. In Type I, ionized gases form a thin, usually straight tail, sometimes millions of kilometers long. (The tail of the Great Comet of 1843 stretched out more than 136 million mi [220 million km].) In fact, the tails of comets are the largest measured entities in the solar system. The ion tail, glowing with incredible brightness, does not trail behind but is blown away from the head in a direction almost opposite the Sun by the "solar wind," a continual flow of magnetized plasma emitted by the Sun. The head collides with this plasma, which wraps around the nucleus, pulling the ionized particles with it. Depending on its position to the Sun, the tail may even be traveling almost ahead of the nucleus. A Type II tail is usually shorter and wider, and curves slightly because the heavier particles are carried away at a slower rate. The Great Comet of 1744 actually displayed six brilliant tails fanning above the horizon like peacock feathers.

Comet Hale-Bopp, which streamed across the skies in 1997, boasted a new feature: a third tail composed of electrically neutral sodium atoms. When completely observed using instruments with spectral filters that eliminated all but the yellow light emitted by fluorescing sodium atoms, the tail was more than 370,000 miles wide (600,000 km) and 31 million miles long (50 million km), streaming in a direction close but slightly different to that of the ion tail. Although the exact mechanism is not understood, the tail is thought to be formed of sodium atoms released by dust particles in the coma.

Comets may strike planets without leaving an **impact crater**. The atmospheric energy released by comet vaporization in the atmosphere can, however, be more powerful than a nuclear explosion. The Tunguska event in Siberia in 1908 is thought to have been the result of a comet or stony meteoroid explosion above the ground. In 1979, a United States Air Force space-test satellite took the first photograph of a comet colliding with the Sun. Late in 1994, the fragmented comet Shoemaker-Levy made spectacular serial collisions with Jupiter.

Some scientists argue that molecules released by comets' vaporized gases may have supplied important molecules in Earth's early atmosphere. When exposed to the Sun's radiation, these molecules began the formation of biochemical compounds that actually began the process of life on Earth—or gave a huge "jump-start" to the evolution of biomolcules. During the recent passage of Hale-Bopp, for example, scientists discovered a variety of complex organic chemicals in the comet.

Some aspects of this theory gained evidence from data gathered by the Polar spacecraft, launched by NASA in 1996. According to some interpretations of observations by the probe, comet-like objects up to 30–40 ft (9–12 m) in diameter may be hitting the atmosphere at the astounding rate of up to 43,000 per day. These cosmic snowballs usually disintegrate in the upper atmosphere, their content liquids and gases entering the **weather** cycle and eventually reaching the terrestrial surface as **precipitation**. Other scientists argue that the evidence of "snowballs" from space is an artifact of instrument background noise or interference.

In a pair of space missions planned for the early part of the twenty-first century, space probes will rendezvous with a pair of short-period comets, hopefully to help scientists reach a better understanding of the **physics** of comets. In 2004, NASA's Stardust mission plans to capture dust from the tail of Comet Wild 2, returning the samples to Earth for analysis. In 2011, the European Space Agency's Rosetta mission will rendezvous with Comet Wirtanen on its trip around the Sun. The Rosetta spacecraft will orbit the comet and send a probe to the surface.

See also Astronomy; Big Bang theory; Impact crater

COMPACTION • *see* LITHIFICATION

CONDENSATION

Condensation occurs when one of the three states of matter in which a gaseous (vapor) substance transforms into a liquid. It is the reverse of vaporization. As a vapor cools, it gives off energy in the form of latent heat. The release of heat causes each vapor molecule to shrink and move more slowly. Strong intermolecular forces (kinetic-molecular theory of gases) push the smaller gas molecules together; the bonding initiates the transformation into a denser, liquid form called condensate.

Condensation can occur from cooling processes such as distillation and steam engine production, or by exerting pressure in a manner that reduces the volume of the gas. Evidence of condensate is often found on a bathroom mirror after a hot shower, or on the outside of a "sweating" soda can as it warms to room **temperature**. Meteorological phenomena such as

clouds, **fog**, and dew are also a result of condensation. Clouds form when rising hot air collides with air in cooler elevations.

In **chemistry**, condensation is defined as a reaction involving the joining of atoms in the same or different molecules. Chemists often use the process of condensation to eliminate simple molecules, such as **water** or alcohol, to form a heavier, more complex compound.

See also Evaporation; Hydrologic cycle

CONGLOMERATE ROCK • *see* ROCK

CONSTELLATIONS • *see* CELESTIAL SPHERE: THE APPARENT MOVEMENTS OF THE SUN, MOON, PLANETS, AND STARS

CONTACT AUREOLE • *see* METAMORPHISM

CONTACT METAMORPHISM • *see* METAMORPHISM

CONTINENTAL CRUST • *see* CRUST

CONTINENTAL DIVIDE

A continental divide is a topographic feature separating streams that flow towards opposite sides of a continent. It is a continental scale version of the topographic divides that separate **drainage basins** of all scales.

In the conterminous United States and Canada, the continental divide follows an irregular course from the Basin and Range and Colorado Plateau physiographic provinces of New Mexico north through the Rocky Mountains, the Yellowstone region, and the Canadian Rockies. **Water** in streams to the west of the continental divide flows toward the Pacific Ocean, whereas that to the east of the continental divide flows toward the Atlantic Ocean. In Alaska, however, the continental divide marks the boundary between **rivers** flowing north and west to the Arctic Ocean and those flowing south and west into the Bering Sea.

Continental divides are often associated with mountainous terrain. Elevations along the continental divide through the conterminous United States, however, range from approximately 1400 meters above sea level in the **Basin and Range topography** of southern New Mexico to more than 4000 meters above sea level in the Rocky Mountains of Colorado and Wyoming.

A common, but inaccurate, notion is that **precipitation** falling on different sides of the divide necessarily travels to different **oceans**. Some precipitation that falls as snow, however, may be sublimated. Snowmelt or water that falls as rain may either evaporate or be transpired by vegetation after percolating into the **soil**. In either of those cases, the water may not travel to any ocean until it falls again as precipitation. In the extreme case of internally drained basins common to arid regions such as the American Southwest, virtually all water flows towards the center of the basins and is removed through **evaporation**, transpiration, and infiltration. Water that infiltrates deep enough to recharge underlying aquifers may ultimately be discharged on the opposite side of the continental divide because, although **groundwater** divides do exist, they do not necessarily correspond exactly to topographic divides. Humans can also play a role, most notably by constructing diversion tunnels through which water is carried from one side of the continental divide to the other as part of water supply projects. Therefore, it is best to restrict the usage of the term continental divide to a topographic divide that separates streams flowing towards opposite sides of the continent than to include speculations about the ultimate fate of individual drops of water.

Aerial view of the continental divide in Colorado. © *Dean Conger/Corbis. Reproduced by permission.*

See also Drainage basins and drainage patterns; Freshwater; Hydrologic cycle; Landscape evolution; Precipitation; Runoff

CONTINENTAL DRIFT THEORY

Continental drift, in the context of the modern theory of **plate tectonics**, is explained by the movement of **lithospheric plates** over the **asthenosphere** (the molten, ductile, upper portion of the earth's mantle). Precisely used, the term continental drift is actually rooted in antiquated concepts regarding the structure of the earth. Modern geophyicists and geologists explain the movement or drift of the continents within the context of plate tectonic theory. The visible continents, a part of the lithospheric plates upon which they ride, shift slowly over time as a result of the forces driving plate tectonics. Moreover, plate tectonic theory is so robust in its ability to explain and predict geological processes that it is equivalent in many regards to the fundamental and unifying principles of **evolution** in biology, and nucleosynthesis in **physics** and **chemistry**.

The original theory of continental drift made the improbable assertion that the continents moved through and across an underlying oceanic **crust** much as **ice** floats and drifts through **water**. Eventually multiple lines of evidence allowed modern tectonic theory to replace continental drift theory.

Based upon centuries of cartographic depictions that allowed a good fit between the Western coast of **Africa** and the Eastern coast of South America—in 1858, French geographer Antonio Snider- Pellegrini, published a work asserting that the two continents had once been part of larger single continent ruptured by the creation and intervention of the Atlantic Ocean.

In the 1920s, German geophysicist Alfred Wegener's writings advanced the hypothesis of continental drift depicting the movement of continents through an underlying oceanic crust.

Wegener's hypothesis met with wide skepticism but found support and development in the work and writings of South African geologist Alexander Du Toit who discovered a similarity in the **fossils** found on the coasts of Africa and **South America** that were seemingly derived from a common source. Other scientists also attempted to explain **orogeny** (mountain building) as resulting from Wegener's continental drift.

Wegener's initial continental drift assertions were based upon the geometric fit of the displaced continents and the similarity of **rock** ages and Paleozoic fossils in corresponding bands or zones in adjacent or corresponding geographic areas. Wegener also argued that the evidence of Paleozoic **glaciation** in South Africa, South America, India and Australia—sites far removed from estimates of the geographical extent of glaciation—argued strongly for continental drift

The technological advances necessitated by the Second World War made possible the accumulation of significant evidence regarding Wegener's hypothesis, eventually refining and supplanting Wegener's theory of continental drift with modern plate tectonic theory. Although Wegener's theory accounted for much of the then existing geological evidence, Wegener's hypothesis was specifically unable to provide a verifiable or satisfying mechanism by which continents—with all of their bulk and drag—could move over an underlying mantle that was solid enough in composition to be able to reflect seismic S- waves.

In his 1960 publication, *History of Ocean Basins*, geologist and U.S. Navy Admiral Harry Hess (1906–1969) asserted that thermal convection currents in the athenosphere provided the driving force behind plate tectonics. The degree with which the earlier geological community resisted acceptance of Wegener's theory of continental drift is clearly demonstrated by the fact that Hess's assertion of thermal currents was drawn from work done by Author Holmes in the 1930s.

See also Earth, interior structure; Hotspots; Sea-floor spreading; Seismology

CONTINENTAL GLACIER • *see* GLACIERS

CONTINENTAL SHELF

The continental shelf is a gently sloping and relatively flat extension of a continent that is covered by the **oceans**. Seaward, the shelf ends abruptly at the shelf break, the boundary that separates the shelf from the continental slope.

The shelf occupies only 7% of the total ocean floor. The average slope of the shelf is about 10 ft per mile (1.9 m per km). That is, for every one kilometer of distance, the shelf drops 1.9 m in elevation until the shelf break is reached. The average depth of the shelf break is 440 ft (135 m). The greatest depth is found off **Antarctica** (1,150 ft [350 m]), where the great weight of the **ice** on the Antarctic continent pushes the **crust** downward. The average width of the shelf is 43 mi (70 km) and varies from tens of meters to approximately 800 mi (1,300 km) depending on location. The widest shelves are in the Arctic Ocean off the northern coasts of Siberia and **North America**. Some of the narrowest shelves are found off the tectonically active western coasts of North and **South America**.

The shelf's gentle slope and relatively flat terrain are the result of **erosion** and sediment deposition during the periodic fall and rise of the sea over the shelf in the last 1.6 million years. The changes in sea level were caused by the advance and retreat of **glaciers** on land over the same time period. During the last glacial period (approximately 18,000 years ago), sea level was 300–400 ft (90–120 m) lower than present and the shoreline was much farther offshore, exposing the shelf to the atmosphere. During lowered sea level, land plants and animals, including humans and their ancestors, lived on the shelf. Their remains are often found at the bottom of the ocean. For example, 12,000 year old bones of mastodons, extinct relatives of the elephant, have been recovered off the coast of the northeastern United States.

Continental shelves contain valuable resources, such as oil and gas and **minerals**. Oil and gas are formed from organic material that accumulates on the continental shelf. Over time the material is buried and transformed to oil and gas by heat and pressure. The oil and gas moves upward and is concentrated beneath geologic traps. Oil and gas is found on the continental shelf off the coasts of California and Louisiana, for example. Minerals come from rocks on land and are carried to the ocean by **rivers**. The minerals were deposited in river channels and beaches on the exposed continental shelf and sorted (concentrated) by waves and river currents, due to their different densities. Over time as the sea level rose, these minerals were again sorted by waves and ocean currents and finally deposited. The different colored bands of **sand** that one can see on a beach are an example of density sorting by waves. The concentrated minerals are often in sufficient enough quantities to be mined. Examples of important minerals on the shelf are diamonds, chromite (chromium ore), ilmenite (titanium ore), magnetite (**iron** ore), platinum, and gold.

See also Glaciation; Ice ages; Sedimentation; Wave motions

CONVECTION (UPDRAFTS AND DOWNDRAFTS)

Convection is the vertical transfer of mass, heat, or other properties in a fluid or substance that undergoes fluid-like dynamics. Convection takes place in the atmosphere, in the **oceans**, and in Earth's molten subcrustal **asthenosphere**. Convective currents of air in the atmosphere are referred to as updrafts and downdrafts.

In addition to heat transfer, convention can be driven by other properties (e.g., salinity, density, etc.).

Convection in the mantle drives motion of the **lithospheric plates**. This convection is, in part, caused by **temperature** differences caused by the radioactive decay of the naturally radioactive elements uranium, thorium, potassium.

The temperature differences in **water** cause ocean currents that vertically mix masses of water at different temperatures. In the atmosphere, convection drives the vertical transport of air both upward and downward. In both cases, convection acts toward equilibrium and the lowest energy state by allowing the properties of the differential air or water masses to mix.

Thermal convection is one of the major forces in atmospheric dynamics and greatly contributes to, and directly influences, the development of **clouds** and storm systems. Convective air currents of rising warm and moist air allow a transfer of sensible and latent heat energy from the surface to the upper atmosphere.

One meteorological hypothesis, the convection theory of cyclones, asserts that convection resulting from very high levels of surface heating can be so strong that the current of air can attain cyclonic velocities and **rotation**.

Convection with the earth's mantle results from differential temperatures in mantle materials. In part, these differences can manifest as hot spots or convective currents where less dense and warmer mantle materials form slow moving vertical currents in the plastic (viscous or thick fluid-like) mantle. Phase change differences in materials also change their density and buoyancy.

Convective currents in the mantle move slowly (at a maximum, inches per year), but may last millions of years.

See also Adiabatic heating; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pressure; Insolation and total solar irradiation

CONVERGENT PLATE BOUNDARY

In terms of **plate tectonics**, collision boundaries are sites where **lithospheric plates** move together and the resulting compression causes either subduction (where one or both lithospheric plates are driven down and destroyed in the molten mantle) or crustal uplifting that results in **orogeny** (mountain building).

Colliding plates create tremendous force. Although lithospheric plates move very slowly (low velocities of inches per each), the plates have tremendous mass. Accordingly, at collision, each lithospheric plate carries tremendous momentum (the mathematical product of velocity and mass) that provides the energy to cause subduction or uplifting. In addition, the buoyancy properties of the colliding lithospheric plates determine the outcome of the particular collision. Oceanic **crust** is denser than continental crust and is subductable. Continental crust, composed of lighter, less dense materials, is too light to undergo subduction and so overrides oceanic crust or uplifts.

Earth's crust is fractured into approximately 20 lithospheric plates. Each lithospheric plate is composed of a layer of oceanic crust or continental crust superficial to an outer layer of the mantle. Oceanic crust comprises the outer layer of the **lithosphere** lying beneath the **oceans**. Oceanic crust is composed of high-density rocks, such as **olivine** and **basalt**. Continental crust comprises the outer layer of the lithospheric plates containing the existing continents and some undersea features near the continents. Continental crust is composed of lower density rocks such as **granite** and **andesite**. Containing both crust and the upper region of the mantle, lithospheric plates are approximately 60 miles (approximately 100 km) thick. Lithospheric plates may contain various combinations of oceanic and continental crust in mutually exclusive sections (i.e., the outermost layer is either continental or oceanic crust, but not both except at convergent boundaries where subducting oceanic crust can make material contributions of lighter crustal materials to the overriding continental crust). Lithospheric plates move on top of the **asthenosphere** (the outer plastically deforming region of Earth's mantle).

At convergent boundaries, lithospheric plates move together in collision zones where crust is either destroyed by subduction or uplifted to form **mountain chains**. In zones of convergence, compressional forces (i.e., compression of lithospheric plate material) dominates.

When oceanic crust collides with oceanic crust, both subduct to form an oceanic trench (e.g., Marianas trench). When oceanic crust collides with continental crust, the oceanic crust subducts under the lighter continental crust and both pushes the continental crust upward into mountain chains (e.g., the Andes). The contribution of molten material from the subduction crust contributes to the volcanic arcs found along the Pacific Rim. Because continental crust does not subduct, when continental crust collides with continental crust, there is a uplift of both crusts (e.g., the ongoing collision of India with **Asia** that continues to push the Himalayas upward by about a centimeter a year. Given the expanse of **geologic time**, even modest geomorphologic changes—measured in inches or centimeters a year—can result in substantial changes over millions of years.

At triple points where three plates converge (e.g., where the Philippine sea plate merges into the North American and Pacific plate **subduction zone**), the situation becomes more complex.

Convergent plate boundaries are, of course, three-dimensional. Because Earth is an oblate sphere, lithospheric plates are not flat, but are curved and fractured into curved sections akin to the peeled sections of an orange. Convergent movement of lithospheric plates can best be conceptualized by the movement together of those peeled sections over a curved surface.

Because Earth's diameter remains constant, there is no net creation or destruction of lithospheric plates and so the amount of crust created at divergent boundaries is balanced by an equal destruction or uplifting of crust at convergent lithospheric plate boundaries.

See also Divergent plate boundary; Earth, interior structure; Earthquakes; Geologic time; Mohorovicic discontinuity (Moho); Subduction zone

COOK, JAMES (1728-1779)

English explorer

James Cook was one of the foremost figures of the Age of Exploration. During his career, Cook circumnavigated the globe twice, and captained three voyages of discovery for England. Cook made significant contributions to the fields of surveying, **cartography**, advanced mathematics, **astronomy**, and navigation. The detailed records of his voyages and contacts with various native peoples are considered the first anthropological survey of the Pacific islands, **Australia**, and New Zealand. Cook's voyages sparked European and American interest in Pacific colonization.

James Cook was born in Marton-in-Cleveland, Yorkshire, England. As a youth, he received a modest education, but was a dedicated self-study of mathematics, surveying, and cartography. Cook was apprenticed to a small shop owner, but later left his apprenticeship to join a merchant collier fleet at Whitby. Cook earned his mate's certificate, but his merchant career was cut short by his decision to enlist with the Royal Navy in 1755 at the outbreak of the Seven Year's War (also known as the French and Indian War, 1756–1763).

Cook was sent to America in 1756 as not only seaman, but as a cartographer. His first charge was to conduct soundings and draw charts of the St. Lawrence River. Cook's charts were later used by British forces for their attack on Quebec. He was next named surveyor of New Foundland and carried out that project until 1767. Cook's maps were so precise that many were used for a century.

As the Cook gained renown for his cartography, he also submitted papers to the Royal Academy on astronomical observation and navigation. His work on determining location using the **moon** commanded the attention of not only scholars, but also the British government. In 1766, Cook was appointed to command an expedition to the Pacific, the first of three great voyages. The stated purpose of Cook's Pacific expedition was to observe and document the transit of Venus across the **Sun** during an **eclipse** on June 3, 1779, as part of a scientific endeavor to calculate the distance from Earth to the Sun. At the completion of that task, Cook continued to record significant discoveries. In the South Pacific, he discovered and named the Society Islands. Cook then sailed to New Zealand, which he reported upon favorably as a potential site for British colonization despite the lack of domesticated animals. Venturing from New Zealand, Cook sailed to the eastern coast of Australia and charted the coastline before claiming the land for Britain. On the return voyage, Cook's crew was stricken with disease, a common occurrence at sea then. One-third of his crew died from malarial fever, scurvy, and dysentery.

Cook was scarcely back in Britain for a year before he received his next appointment. He was granted two ships, the *Adventure* and the *Resolution*, and sent back to the Pacific to further complete the exploration of the Southern Hemisphere. Cook was charged with finding a southern continent, which was thought to exist in the extreme South Pacific; the mysterious continent was supposed to be temperate with fertile land. Cook left Britain in 1772 and sailed for the extreme southern Atlantic. Pushing his way through **freezing** temperatures and **ice** flows, cook sailed along the edge of **Antarctica**. The frozen Antarctic was certainly not the fabled southern continent. Cook's circumnavigation of the southern Pole put an end to the legend. Cook again stopped in New Zealand, this time introducing some European plants and domestic animals into the indigenous landscape. He discovered, charted, and named several more islands as he finished his journey.

On his second voyage, Cook also made pioneering provisions for his crew. To avoid the scourge of disease that had plagued the second half of his first voyage, Cook brought an ample supply of lemons aboard and served sauerkraut to the crew in an attempt to ward off scurvy and fevers. The experiment worked; Cook lost only one crewman to disease.

Cook embarked on his third and final voyage in 1776. Instead of returning to the South Pacific, Cook turned his efforts to the Pacific coast of **North America** in search of a northern passage that connected the Atlantic and Pacific **Oceans**. He created detailed maps of the Pacific Coast that were used on later expeditions, including the Lewis and Clark expedition. However, Cook failed to locate the Columbia River and thought that Victoria Island was part of the mainland. Despite these flaws in his cartography, Cook's expedition, and his records of contact with various native peoples who possessed great natural resources, created a new interest in trade and settlement in the Pacific Northwest.

As Cook ventured to the North American Coast, he discovered present-day Hawaii, which he dubbed the Sandwich Islands, in March of 1778. Cook enjoyed a record of very amicable relationships with the native peoples he encountered on his expeditions. His initial contact with the peoples of the Sandwich Islands were no exception; after a time however, Cook felt that relations were beginning to sour so he pulled up anchor and sailed away. Two days later, the foremast of the *Resolution* snapped and Cook returned to the Sandwich

Islands. The native population grew increasingly hostile and stole one of Cook's cutters. In retaliation, Cook took the tribal chief hostage in order to facilitate an exchange. In the ensuing commotion, a shot was fired and the natives threw stones, attacking Cook and his crew. Cook died in the altercation at the age of 51.

COPERNICUS, NICOLAS (1473-1543)

Polish astronomer and mathematician

Nicolas Copernicus was born into a well-to-do family on February 19, 1473. His father, a copper merchant, died when Copernicus was 10, and the boy was taken in by an uncle who was a prince and bishop.

Copernicus was able to afford an excellent education. He entered the University of Cracow in 1491 and studied mathematics and painting. In 1496, he went to Italy for 10 years where he studied medicine and religious law. Two things happened in the year 1500 that influenced Copernicus; he attended a conference in Rome dealing with calendar reform and, on November 6, 1500, he witnessed a lunar **eclipse**.

The tables of planetary positions that were in use at the time were complex and inaccurate. Predicting the positions of the planets over long periods of time was haphazard at best, and the **seasons** were out of step with the position of the **Sun**. Copernicus realized that tables of planetary positions could be calculated much more easily, and accurately, if he made the assumption that the Sun, not Earth, was the center of the **solar system** and that the planets, including Earth, orbited the Sun. He first proposed this theory in 1507.

Copernicus was not the first person to introduce such a radical concept. Aristarchus had come up with the idea in ancient Greece long before, but the teachings of **Ptolemy** had been dominant for 1,300 years. Ptolemy claimed the earth was at the center of the universe, and all the planets (including the Sun and **Moon**) were attached to invisible celestial spheres that rotated around the earth.

Copernicus not only wished to refute Ptolemy's universe, he claimed that Earth itself was very small and unimportant compared to the vast vault of the stars. This marked the beginning of the end of the influence of the ancient Greek scientists.

Copernicus made an incorrect assumption about planetary orbits; he decided they were perfectly circular. Because of this, he found it necessary to use some of Ptolemy's cumbersome epicycles (smaller orbits centered on the larger ones) to reduce the discrepancy between his predicted orbits and those observed. It wasn't until Johannes Kepler's time that this was corrected and the true nature of planetary orbits was understood.

Even so, the heliocentric model developed by Copernicus fit the observed data better than the ancient Greek concept. For example, the periodic "backward" motion in the sky of the planets Mars, Jupiter, and Saturn and the lack of such motion for Mercury and Venus was more readily explained by the fact that the former planets' orbits were outside of Earth's. Thus, the earth "overtook" them as it circled the Sun. Planetary positions could also be predicted much more accurately using Copernicus' model.

Nicolas Copernicus. ***Library of Congress.***

Copernicus was reluctant to make his ideas public. He realized his theory not only contradicted the Greek scientists, it went against the teachings of the Church, the consequences of which could be severe. In 1530, he allowed a summary of his ideas to circulate among scholars, who received it with great enthusiasm, but it was not until just shortly before his death in 1543 that his entire book was published. It took the efforts of the mathematician Rheticus to convince Copernicus to grant him permission to print it. Unfortunately, Rheticus had fallen afoul of official doctrine himself, and found it wise to leave town. Overseeing the publication for Copernicus's book was transferred to the hands of a Lutheran minister named Andreas Osiander (1498–1552).

Osiander now found he was in a tight spot; Martin Luther (1483–1546) had come out firmly against Copernicus' new theory, and Osiander was obligated to follow him. "This Fool wants to turn the whole Art of Astronomy upside down," Luther had said. Copernicus had dedicated his book to Pope Paul III, perhaps to gain favor, but Osiander went one step further; he wrote a preface in which he stated the heliocentric theory was not being presented as actual fact, but just as a concept to allow for better calculations of planetary positions. He did not sign his name to the preface, making it appear that

Copernicus had written it and was debunking his own theory. Copernicus, suffering from a stroke and close to death, could do nothing to defend himself. It is said he died only hours after seeing the first copy of the book. Kepler discovered the truth about the preface in 1609 and exonerated Copernicus.

The immediate reaction to the book, *De Revolutionibus Orbium Coelestium* (Revolution of the heavenly spheres), was subdued. This was primarily due to Osiander's preface, which weakened Copernicus' reputation. In addition, only a limited number of books were printed, they were very expensive and, consequently, had limited circulation. The book did achieve a number of converts, but one had to be a mathematician to fully understand the theories. Still, it was placed on the Roman Catholic Church's list of prohibited books where it remained until 1835.

Almost as significant as proving the heliocentric solar system was possible, was Copernicus's questioning of the ancient Greek scientists. Ptolemy had bent the facts to fit his preconceived theory and his teachings had been accepted, without question, for centuries. Copernicus, on the other hand, did his best to develop his theory to match observed facts, foreshadowing the dawning of modern **scientific method**.

CORAL REEFS AND CORALS

Reefs are found in the **fossil record** and are thought to be about two billion years old. These reefs were built by calcareous algae and not corals. The first true corals did not appear until about 300–500 million years ago. They apparently flourished until a devastating extinction occurred killing many groups of corals. Most of the corals that compose extant (still living) reefs were found around 65 million years ago. They are still a vital part of the living environment. In addition to their ecological role as a foundation for a wide variety of life forms, the coral reefs have become a haven for tourists and scuba divers.

Corals are animals that belong to the monophyletic group called the Cnidaria (formerly called a Phylum). They are named for specialized stinging structures that emit long, venomous barbs when stimulated by the presence of prey or danger. Corals are further classified into a smaller subdivision, the Anthozoa. For geologists, the most important characteristic of many corals is their ability to remove calcium from the **water** and redeposit it as a hardened outer casing in the form of calcium carbonate. Because many corals species are colonial, the chambers of the animals grow together forming a larger hardened structure. Over many years, these constructions may merge with others of the same species or with those of different species. The resulting large and diverse colony makes an impressive and rigid structure that spreads across the sea bottom. At this point, it is identified as a reef. Within the reef, there are hiding places for fish and other marine organisms. Organic material is abundant and many species live their entire lives within the confines of the protection the reef provides.

Coral reefs as ecosystems are being endangered by human activities. ***© Stephen Frink/Corbis. Reproduced by permission.***

Corals are believed to live in a symbiotic relationship with species of microscopic algae. As a result, reef corals are rarely found below the photic zone or about 150 feet (46 m). The photic zone is a narrow strip of surface water (about 200 feet) through which sunlight permeates. Below this depth particles in the water prevent light waves from penetrating.

Corals require clear water to flourish. They need as much light energy as possible so the algae in their tissues can thrive. In addition, they prefer areas where wave energy is high. The waves bring floating organic materials, **oxygen**, and nutrients to the corals. Reef-building corals require warm ocean temperatures (68 to 82°F, or 20 to 28°C). Because of this requirement, corals are primarily confined to areas within 30°N and 30°S latitudes. This region includes the tropical and subtropical Western Atlantic and Indo-Pacific **Oceans**. Western Atlantic reefs are found in Bermuda, the Bahamas, the Caribbean Islands, Belize, Florida, and the **Gulf of Mexico**. The Indo-Pacific ocean region extends from the Red Sea and the Persian Gulf through the Indian and Pacific oceans. Reefs have been found as far as the western coast of Panama. The rocky outcrops in some areas of the Gulf of California are also favorable regions for corals. These warm shallow **seas** provide ideal conditions where water temperatures and salinity are high and **carbon dioxide** concentrations are low. In this type of habitat the corals are able to precipitate calcium out of the water.

The colors of the reefs are impressive and add to their beauty. The United States National Oceanographic and Atmospheric Administration describe natural pigments in coral tissue that produce a range of colors including white, red, orange, yellow, green, blue, and purple, along with algae that live within the tissues of some corals that may make the coral appear brown, green, or orange. Unfortunately, this characteristic of some corals has made them prized for their use in jewelry. Removal of living corals for such uses has put many species in danger of extinction or severe harm.

The massive structure of some reefs is especially important to geologists because the colonies can reshape coastal **sedimentation** and deposition regimes. **Barrier islands** provide some of the more spectacular examples of this. As seamounts grow in warm oceans corals land on the emerging **rock** shore and begin their colonies. Over millions of years, the islands may move and sink because of **plate tectonics**. The corals continue to grow on top of one another as they attempt to stay near the surface. The reef expands until large areas of coastline are bordered by the reefs. Waves are slowed by the reefs and any sediment they carry is dropped on the ocean side of the reef. The water that flows over the coral and toward the beach has little energy and is relatively clear. Any sediment it carries is fine-grained and deposited in a space called a lagoon. Lagoons are warm bodies of water that lie between the reef and shore. The waters are calm and warm. Numerous species of plants and animals live in a lagoon. They are favored locations of tourists for swimming and snorkeling and provide ideal spots for recreation.

The continuing cycle of growth of the corals and deposition of sediments are well documented in the fossil record. Reefs sometimes grow to a massive size, and are often identified in rocks such as those found in the Big Bend National Park in Texas. The El Capitan Reef is an exceptional example of such a structure. This is one of the types of evidence geologists use to reconstruct **climate** in various regions of the globe.

Coral reefs are disappearing in many places around Earth. Projects, such as those in Florida where old ships are sunk to provide new surface **area** for coral colonies to grow, are helping save the reefs from destruction by divers and fishing boats. **Water pollution** and disease still threaten many species. Without coral reefs, entire marine ecosystems may vanish, and an ancient geological and biological system might disappear from Earth.

See also Great Barrier Reef; Oceanography

CORIOLIS EFFECT

The Coriolis effect (sometimes called the Coriolis force) is the apparent deflection of air masses and fluids caused by Earth's **rotation**. Named after the French mathematician Gustave-Gaspard Coriolis, (1792-1843), who developed the concept in 1835, the Coriolis force is a pseudoforce (false force) and should properly be termed the Coriolis effect. As a result of the Coriolis effect, there is an apparent deflection of all matter in motion to the right of their path in the Northern Hemisphere, and to the left in the Southern Hemisphere. In the Northern Hemisphere, air is deflected counterclockwise (to right of its established path of motion) as it moves inward toward a low-pressure **area** (zone of convergence). In the Northern Hemisphere, air is deflected clockwise (again, to the right of its established path of motion) as it moves outward toward a low-pressure area (zone of convergence). These deflections and rotations are reversed in the Southern Hemisphere.

The Coriolis effect is a mechanical principle demonstrating that, on a rotating solid body, an inertial force acts on the body at right angles to its direction of motion. The Coriolis effect is based on the classic laws of motion introduced by English physicist and mathematician **Sir Isaac Newton** (1642-1727) in his work, *Philosophiae Naturalis Principia Mathematica* (Mathematical principles of natural philosophy).

Within its rotating coordinate system, the object acted on by the Coriolis effect appears to deflect off of its path of motion. This deflection is not real. It only appears to happen because the coordinate system that establishes a frame of reference for the observer is also rotating. The Coriolis effect is due to the motion of a rotating frame of reference (e.g., Earth's rotation).

For example, if a missile is launched northward from the equator. The missile will land to the right of a directly northward target because, when launched, the missile moving along with the ground at the equator moves faster to the east than its direct northward target. Conversely, if a missile were fired from the North Pole to a directly southward target (a target on a great circle that also passed through the South Pole) will also land to the right of its intended target because during the missile's flight the target area has moved farther to the east faster. In the Southern Hemisphere these deflections are reversed (i.e., objects are deflected to the left).

The Coriolis effect is important to virtually all sciences that relate to Earth and planetary motions. It is critical to the dynamics of the atmosphere including the motions of winds and storms. In **oceanography**, it helps explains the motions of oceanic currents. Accounting for the Coriolis effect is critical in planning the motions of aircraft and the launch and recovery of spacecraft. In **astronomy** and astrophysics the Coriolis effect explains the rotation of sunspots.

A popular canard (a popular, widely accepted, but false premise) is that **water** in sinks and toilet bowls drains away in counterclockwise or clockwise motion depending on whether the drain is located in the northern or Southern Hemisphere. The fact is that the Coriolis effect acts only on fluids over great distances or long lengths of time, but is not great enough to produce these defections. These deflections are caused by other factors (drain shape, initial water velocity, etc.)

See also Air masses and fronts; Atmospheric circulation; Ocean circulation and currents; Weather and climate; Wind

False color imaging of a solar flare. ***U.S. National Aeronautics and Space Administration (NASA).***

CORONAL EJECTIONS AND MAGNETIC STORMS

Coronal mass ejections (CME) are explosive and violent eruptions of charged, magnetic field-inducing particles and gas from the Sun's outer coronal layer. The ejection from the Sun's corona can be massive (e.g., estimates of CME mass often range in the billions of tons. Ejections propel particles in specific directions, some directly crossing Earth's orbital position, at velocities up to 1200 miles per second (1,931 km per second) or 4,320,000 miles per hour in an ionized plasma (also known as the solar **wind**). Solar CMEs that are Earth directed disrupt and distort Earth's **magnetic field** and result in geomagnetic storms.

Although the solar wind is continuous, CMEs reflect large-scale increases in wind (i.e., particle) mass and velocity that are capable of generating geomagnetic storms.

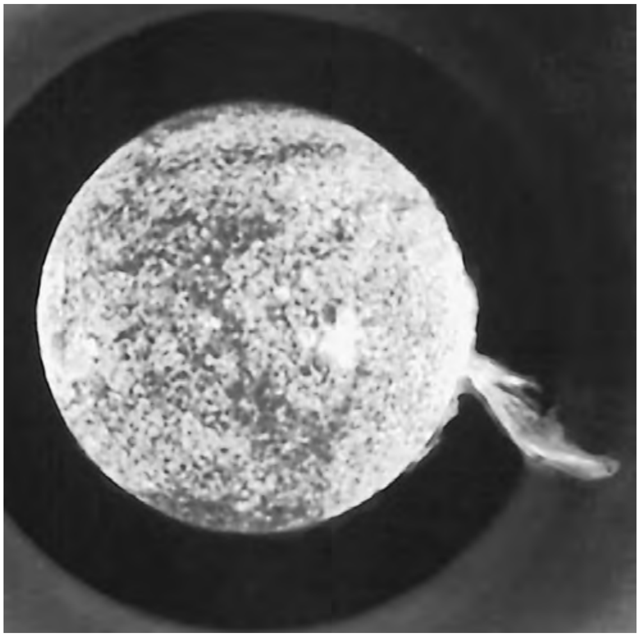
Solar coronal ejections and magnetic storms interact with Earth's magnetosphere to produce spectacular auroral displays. Intense storms may interfere with communications and preclude data transfer from Earth orbiting satellites.

Solar coronal ejections and magnetic storms provide the charged particles that result in the northern and southern lights—Aurora Borealis and Aurora Australialis—electromagnetic phenomena that usually occur near Earth's polar regions. The auroras result from the interaction of Earth's magnetic field with ionic gas particles, protons, and electrons streaming outward in the solar wind.

The rate of solar coronal ejections is correlated to solar sunspot activity that cycles between maximum levels of activity (i.e., the solar maximum) approximately every 11 years. During solar maximums, it is not uncommon to observe multiple coronal ejections per day. At solar minimum, one solar coronal ejection per day is normal.

Earth's core structure provides it with a relatively strong internal magnetic field (oriented about 10–12 degrees from the **polar axis**). Earth's magnetosphere protects the earth from bombardment by Comes by deflecting and modifying the solar wind. At the interface of Earth's magentosphere and the solar wind there is a "bow wave" or magnetic shock wave to form a magnetosheath protecting the underlying magnetosphere that extends into Earth's **ionosphere**.

Coronal mass ejections (CMEs) not only interact with Earth's magnetic field, they also interact with each other. Stronger or faster ejections may subsume prior weaker ejections directed at the same region of **space** in a process known as CME cannibalization. Accordingly, the strength of magnetic storms on Earth may not directly correlate to observed



Skylab image of the Sun showing a solar flare. ***U.S. National Aeronautics and Space Administration (NASA).***

coronal ejections. In addition, CME cannibalization can alter predicted arrival time of geomagnetic storms because the interacting CMEs can change the eruption velocity.

See also Atmospheric chemistry; Atmospheric composition and structure; Atomic theory; Atoms; Bohr model; Chemical elements; Electricity and magnetism; Electromagnetic spectrum; Quantum electrodynamics (QED); Solar sunspot cycles

CORRELATION (GEOLOGY)

In **geology**, the term correlation refers to the methods by which the age relationship between various strata of Earth's **crust** is established. Such relationships can be established, in general, in one of two ways: by comparing the physical characteristics of strata with each other (physical correlation); and by comparing the type of **fossils** found in various strata (fossil correlation).

Correlation is an important geological technique because it provides information with regard to changes that have taken place at various times in Earth history. It also provides clues as to the times at which such changes have occurred. One result of correlational studies has been the development of a **geologic time** scale that separates Earth history into a number of discrete time blocks known as eras, periods, and epochs.

Sedimentary rocks provide information about Earth history that is generally not available from igneous or metamorphic rocks. For example, suppose that for many millions of years a river has emptied into an ocean, laying down, or depositing, sediments eroded from the land. During that period of time, layers of sediments would have collected one on top of the other at the mouth of the river. These layers of sediments are likely to be very different from each other, depending on a number of factors, such as the course followed by the river, the **climate** of the **area**, the **rock** types exposed along the river course, and many other geological factors in the region. One of the most obvious differences in layers is thickness. Layers of sedimentary rock may range in thickness from less than an inch to many feet.

Sedimentary layers that are identifiably different from each other are called beds or strata. In many places on Earth's surface, dozens of strata are stacked one on top of each other. Strata are often separated from each other by relatively well-defined surfaces known as **bedding** planes.

In 1669, the Danish physician and theologian Nicolaus Steno (1638–1686) made a seemingly obvious assertion about the nature of sedimentary strata. Steno stated that in any sequence of sedimentary rocks, any one layer (stratum) is younger than the layer below it and older than the layer above it. Steno's discovery is now known as the law of **superposition**.

The law of superposition applies only to sedimentary rocks that have not been overturned by geologic forces. **Igneous rocks**, by comparison, may form in any horizontal sequence whatsoever. A flow of **magma** may force itself, for example, underneath, in the middle or, or on top of an existing rock stratum. It is very difficult to look back millions of years later, then, and determine the age of the igneous rock compared to rock layers around it.

Using sedimentary rock strata it should be possible, at least in theory, to write the geological history of the continents for the last billion or so years. Some important practical problems, however, prevent the full realization of this goal. For example, in many areas, **erosion** has removed much or most of the sedimentary rock that once existed there. In other places, strata are not clearly exposed to view but, instead, are buried hundreds or thousands of feet beneath the thin layer of **soil** that covers most of Earth's surface.

A few remarkable exceptions exist. A familiar example is the Grand **Canyon**, where the Colorado River has cut through dozens of strata, exposing them to view and making them available for study by geologists. Within the Grand Canyon, a geologist can follow a particular stratum for many miles, noting changes within the stratum and changes between that stratum and its neighbors above and below. One of the characteristics observable in such a case is that a stratum often changes in thickness from one edge to another. At the edge where the thickness approaches zero, the stratum may merge into another stratum. This phenomenon is understandable when one considers the way the sediment in the rocks was laid down. At the mouth of a river, for example, the accumulation of sediments is likely to be greatest at the mouth itself, with decreasing thickness at greater distances into the lake or ocean. The principle of lateral continuity describes this phenomenon, namely that strata are three-dimensional features that extend outward in all directions, merging with adjacent deposits at their edges.

Human activity also exposes strata to view. When a highway is constructed through a mountainous (or hilly) area, for example, parts of a mountainside may be excavated, revealing various sedimentary rock strata. These strata can then be studied to discover the correlation among them and with strata in other areas.

Another problem is that strata are sometimes disrupted by earth movements. For example, an **earthquake** may lift one block of Earth's crust over an adjacent block or may shift it horizontally in comparison to the second block. The correlation between adjacent strata may then be difficult to determine.

Physical correlation is accomplished by using a number of criteria. For example, the color, grain size, and type of **minerals** contained within a stratum make it possible for geologists to classify a particular stratum quite specifically. This allows them to match up portions of that stratum in regions that are physically separated from each other. In the American West, for example, some strata have been found to cover large parts of two or more states although they are physically exposed in only a few specific regions.

The stratum tends to have one set of characteristics in one region, which gradually changes into another set of characteristics farther along in the stratum. Those characteristics also change, at some distance farther along, into yet another set of characteristics. Rocks with a particular set of characteristics are called a facies. Facies changes, changes in the characteristics of a stratum or series of strata, are important clues to Earth history. If, for example, a geologist finds that the facies in a particular stratum change from a **limestone** to a shale to a **sandstone** over a distance of a few miles, the geologist knows that limestone is laid down on a sea bottom, shale is formed from compacted mud, and sandstone is formed when **sand** is compressed. The limestone to shale to sandstone facies pattern may allow an astute geologist to reconstruct what Earth's surface looked like when this particular stratum was formed. For example, knowing these rocks were laid down in adjacent environments, the geologist might consider that the limestone was deposited on a coral reef, the shale in a quiet lagoon or coastal swamp, and the sandstone in a nearby beach. So facies changes indicate differences in the environments in which adjacent facies were deposited.

One of the most important discoveries in the science of correlation was made by the English surveyor **William Smith** (1769–1839) in the 1810s. One of Smith's jobs involved the excavation of land for canals being constructed outside of London. As sedimentary rocks were exposed during this work, Smith found that any given stratum always contained the same set of fossils. Even if the stratum were physically separated by a relatively great distance, the same fossils could always be found in all parts of the stratum.

In 1815, Smith published a map of England and Wales showing the geologic history of the region based on his discovery. The map was based on what Smith called his law of faunal succession. That law says simply that it is possible to identify the sequence in which strata are laid down by examining the fossils they contain. The simplest fossils are the oldest and, therefore, strata that contain simple fossils are older than strata that contain more complex fossils.

The remarkable feature of Smith's discovery is that it appears to be valid over very great distances. That is, suppose that a geologist discovers a stratum of rock in southwestern California that contains fossils A, B, and C. If another stratum of rock in eastern Texas is also discovered that contains the same fossils, the geologist can conclude that it is probably the same stratum—or at least of the same age—as the southwestern California stratum.

The correlational studies described so far allow scientists to estimate the relative ages of strata. If stratum B lies above stratum A, B is the younger of the two. However determining the actual, or absolute, age of strata (for example, 3.5 million years old) is often difficult because the age of a fossil cannot be determined directly. The most useful tool in dating strata is radiometric dating of materials. A radioactive isotope such as uranium-238 decays at a very regular and well-known rate. That rate is known as its **half-life**, the time it takes for one-half of a sample of the isotope to decay. The half-life of uranium-238, for example, is 4.5 billion years. By measuring the concentration of uranium-238 in comparison with the products of its decay (especially lead-206), a scientist can estimate the age of the rock in which the uranium was found. This kind of radioactive dating has made it possible to place specific dates on the ages of strata that have been studied and correlated by other means.

See also Cross cutting; Dating methods; Field methods in geology; Landscape evolution; Strike and dip

CORROSION

Corrosion is the deterioration of a material, or of its properties, as a consequence of reaction with the environment.

In addition to corrosion of metals—the effects of **soil**, atmosphere, chemicals, and **temperature** serve as agents of corrosion for a number of materials. The need to understand and control corrosion has given rise to the new sciences of corrosion technology and corrosion control, both of which are solidly based upon **chemistry** and **geochemistry**.

Perhaps the earliest recognition of corrosion was the effect of seawater and sea atmospheres on ships. Salt **water**, continual dampness, and the growth of marine life such as marine borers, led to the decay of wooden hulls. Because of its toxicity, copper cladding of the hulls was widely used to discourage marine growth. In 1824, to protect the copper from deterioration, the team of English scientists Humphrey Davy (1778-1829) and **Michael Faraday** (1791-1867) applied zinc protector plates to the copper sheathing. This was the first successful application of cathodic protection, in which a more readily oxidized metal is attached to the metal to be protected. This procedure was widely used until hulls were replaced by steel or newer materials.

With the development of the industrial age, and the increased use of **iron**, the oxidation of iron, or rust, forced the development of steels and the search for new **metals** and metal coatings to protect surfaces. This gave birth to the science of corrosion control that involves measures of material selection, inhibition, painting, and novel design.

The corrosion of metals is caused by the electrochemical transfer of electrons from one substance (**oxygen** for example) to another. This may occur from the surfaces of metals in contact, or between a metal and another substance when a moist conductor or electrolyte is present. Depending upon the conditions, various types of corrosion may occur (e.g., general corrosion, intergranular and pitting corrosion, stress corrosion cracking, corrosion fatigue, galvanic and cavitation corrosion, etc.)

Throughout the world, the direct and hidden costs of deterioration due to environmental corrosion amount to billions of dollars per year.

See also Atmospheric chemistry; Atmospheric pollution; Chemical bonds and physical properties; Chemical elements; Weathering and weathering series

COSMIC MICROWAVE BACKGROUND RADIATION

In 1965, American physicists **Arno Penzias** (1933–) and Robert Wilson (1936–) announced the discovery of microwave radiation, which uniformly filled the sky and had a blackbody **temperature** of about 3.5K. The pair had been testing a new radio amplifier that was supposed to be exceptionally quiet. After many attempts to account for all extraneous sources of radio noise, they concluded that there was a general background of radiation at the radio frequency they were using. After discussions with a group led by Robert Dicke at nearby Princeton University it became clear that they had in fact detected remnant radiation from the origin of the universe.

Although neither Dicke's group nor Penzias and Wilson realized it at the time, they had confirmed a prediction made by scientists 17 years earlier. Although the temperature that characterized the detected radiation was somewhat different than predicted, the difference could be accounted for by changes to the accepted structure of the universe discovered between 1948 and 1965. The detection of this radiation and its subsequent verification at other frequencies was taken as confirmation of a central prediction of a **cosmology** known as the Big Bang.

The interpretation of the red-shifts of spectral lines in distant galaxies by American astronomer **Edwin Hubble** (1889–1953) 40 years earlier suggested a Universe that was expanding. One interpretation of that expansion was that the universe had a specific origin in **space** and time. Such a universe would have a very different early structure from the present one.

It was the Russian-American physicist George Gamow (1904–1968) and colleagues who suggested that the early phases of the universe would have been hot and dense enough to sustain nuclear reactions. Following these initial phases, the expanding universe would eventually cool to the point at which the dominant material, hydrogen, would become relatively transparent to light and radio waves. We know that for hydrogen, this occurs when the gas reaches a temperature of between 5,000K–10,000K. From that point on in the **evolution** of the universe, the light and matter would go their separate ways.

As every point in the universe expands away from every other point, any observer in the universe sees all objects receding from him or her. The faster moving objects will appear at greater distances by virtue of their greater speed. Indeed, their speed will be directly proportional to their distance, which is what one expects for material ejected from a particular point in space and time. However, this expansion results from the expansion of space itself, and should not be viewed simply as galaxies rushing headlong away from one another through some absolute space. The space itself expands.

As it does, light traveling through it is stretched, becoming redder and appearing cooler. If one samples that radiation at a later date, it will be characteristic of radiation from a much cooler source. From the rate of expansion of the universe, it is possible to predict what that temperature ought to be. Current values of the expansion rate are completely consistent with the current measured temperature of about 2.7K. The very existence of this radiation is strong evidence supporting the expanding model of the universe championed by Gamow and colleagues and disparagingly named the "Big Bang" cosmology by English astronomer **Sir Fred Hoyle** (1915–2001).

Since its discovery in 1965, the radiation has been carefully studied and found to be a perfect blackbody as expected from theory. Since this radiation represents fossil radiation from the initial Big Bang, any additional motion of the earth around the **Sun**, the Sun around the galactic center, and the galaxy through space should be reflected in a slight asymmetry in the background radiation. The net motion of Earth in some specific direction should be reflected by a slight Doppler shift of the background radiation coming from that direction toward shorter wavelengths.

Doppler shift is the same effect that the police use to ascertain the velocity of approaching vehicles. Of course, there will be a similar shift toward longer wavelengths for light coming from the direction from which we are receding. This effect has been observed indicating a combined peculiar motion of Earth, the Sun and galaxy on the order of 600 km/sec.

Finally, small fluctuations in the background radiation are predicted which eventually led to the formation galaxies and clusters of galaxies. Such fluctuations have been found by the CO(smic) B(ackground) E(xplorer) **Satellite**, launched by NASA in 1989. COBE detected these fluctuations at about 1 part in 105, which was right near the detection limit of the satellite. The details of these fluctuations are crucial to deciding between more refined models of the expanding universe. COBE was decommissioned in 1993, but scientists are still unraveling the information contained in its data.

It is perhaps not too much of an exaggeration to suggest that cosmic background radiation has elevated cosmology from enlightened speculative metaphysics to an actual science. We may expect developments of this emerging science to lead to a definitive description of the evolutionary history of the universe in the near future.

See also Big Bang theory; Cosmic ray; Solar system

COSMIC RAY

The term cosmic ray refers to highly-energetic atomic particles (mostly single protons, some proton-neutron pairs, and occasionally subatomic particles and electrons) that travel through **space** near the speed of light. Physicists divide cosmic rays into two categories: primary and secondary. Primary cosmic rays originate far outside Earth's atmosphere. Secondary cosmic rays are particles produced within Earth's atmosphere as a result of collisions between primary cosmic rays and molecules in the atmosphere.

The existence of cosmic radiation was first discovered in 1912, in experiments performed by the Austrian-American physicist Victor Hess (1883–1964). His experiments were sparked by a desire to better understand phenomena of electric charge. A common instrument of the day for demonstrating such phenomena was the electroscope. An electroscope contains thin metal leaves or wires that separate from one another when they become charged, due to the fact that like charges repel. Eventually the leaves (or wires) lose their charge and collapse back together. It was known that this loss of charge had to be due to the attraction by the leaves of charged particles (ions) in the surrounding air. The leaves would attract those ions having a charge opposite to that of the leaves, due to the fact that opposite charges attract; eventually the accumulation of ions in this way would neutralize the charge that had been acquired by the leaves, and they would cease to repel each other. Scientists wanted to know where these ions came from. It was thought that they must be the result of radiation emanating from Earth's **crust**, since it was known that radiation could produce ions in the air. This led scientists to predict that fewer ions would be present the further one traveled away from Earth's surface. Hess's experiments, in which he took electroscopes high above Earth's surface in a balloon, showed that this was not the case. At high altitudes, the electroscopes lost their charge even faster than they had on the ground, showing that there were more ions in the air and thus, that the radiation responsible for the presence of the ions was stronger at higher altitudes. Hess concluded that there was a radiation coming into our atmosphere from outer space.

As physicists became interested in cosmic radiation, they developed new ways of studying it. The Geiger-Muller counter consists of a wire attached to an electric circuit and suspended in a gaseous chamber. The passage of a cosmic ray through the chamber produces ions in the gas, causing the counter to discharge an electric pulse. Another instrument, the cloud chamber, contains a gas that condenses into vapor droplets around ions when these are produced by the passage of a cosmic ray. In the decades following Hess's discovery, physicists used instruments such as these to learn more about the nature of cosmic radiation.

An **atom** of a particular element consists of a nucleus surrounded by a cloud of electrons, which are negatively charged particles. The nucleus is made up of protons, which have a positive charge, and neutrons, which have no charge. These particles can be further broken down into smaller constituents; all of these particles are known as subatomic particles. Cosmic rays consist of nuclei and of various subatomic particles. Almost all of the primary cosmic rays are nuclei of various atoms. The great majority of these are single protons, which are nuclei of hydrogen atoms. The next most common primary cosmic ray is the nucleus of the helium atom, made up of a proton and a neutron. Hydrogen and helium nuclei make up about 99% of the primary cosmic radiation. The rest consists of nuclei of other elements and of electrons.

When primary cosmic rays enter Earth's atmosphere, they collide with molecules of gases present there. These collisions result in the production of more high-energy subatomic particles of different types; these are the secondary cosmic rays. These include photons, neutrinos, electrons, positrons, and other particles. These particles may in turn collide with other particles, producing still more secondary radiation. If the energy of the primary particle that initiates this process is very high, this cascade of collisions and particle production can become quite extensive. This is known as a shower, air shower, or cascade shower.

The energy of cosmic rays is measured in units called electron volts (abbreviated eV). Primary cosmic rays typically have energies on the order of billions of electron volts. Some are vastly more energetic than this; a few particles have been measured at energies in excess of 10^{19} eV. This is in the neighborhood of the amount of energy required to lift a weight of 2.2 lb (1 kg) to a height of 3.3 ft (1 m). Energy is lost in collisions with other particles, so secondary cosmic rays are typically less energetic than primary ones. The showers of particles described above diminish as the energies of the particles produced decrease. The energy of cosmic rays was first determined by measuring their ability to penetrate substances such as gold or **lead**.

Because cosmic rays are mostly charged particles (some secondary rays such as photons have no charge), they are affected by magnetic fields. The paths of incoming primary cosmic rays are deflected by the earth's **magnetic field**, somewhat in the way that **iron** filings will arrange themselves along the lines of force emitted by a magnet. More energetic particles are deflected less than those having less energy. In the 1930s, it was discovered that more particles come to the earth from the West than from the East. Because of the nature of Earth's magnetic field, this led scientists to the conclusion that most of the incoming cosmic radiation consists of positively charged particles. This was an important step towards the discovery that the primary cosmic rays are mostly bare atomic nuclei, since atomic nuclei carry a positive charge.

The ultimate origin of cosmic radiation is still not completely understood. Some of the radiation is thought to have been produced in the "Big Bang" at the origin of the universe. Other cosmic rays are produced by the **Sun**, particularly during solar disturbances such as solar flares. Exploding stars, called supernovas, are also a source of cosmic rays.

The fact that cosmic ray collisions produce smaller subatomic particles has provided a great deal of insight into the fundamental structure of matter. The construction of experimental equipment such as particle accelerators has been inspired by a desire to reproduce the conditions under which high-energy radiation is produced, in order to gain better experimental control of collisions and the production of particles.

See also Astronomy; Big Bang theory; Cosmic microwave background radiation; Quantum theory and mechanics

COSMOLOGY

Cosmology is the study of the origin, structure and **evolution** of the universe.

The origins of cosmology predate the human written record. The earliest civilizations constructed elaborate myths and folk tales to explain the wanderings of the **Sun**, **Moon,** and stars through the heavens. Ancient Egyptians tied their religious beliefs to celestial objects and Ancient Greek and Roman philosophers debated the composition and shape of the Earth and the Cosmos. For more than 13 centuries, until the Scientific Revolution of the sixteenth and seventeenth centuries, the Greek astronomer Ptolemy's model of an Earth-centered Cosmos composed of concentric crystalline spheres dominated the Western intellectual tradition.

Polish astronomer Nicolaus Copernicus' (1473–1543) reassertion of the once discarded heliocentric (Sun-centered) theory sparked a revival of cosmological thought and work among the astronomers of the time. The advances in empiricism during the early part of the Scientific Revolution, embraced and embodied in the careful observations of Danish astronomer **Tycho Brahe** (1546–1601), found full expression in the mathematical genius of the German astronomer **Johannes Kepler** (1571–1630) whose laws of planetary motion swept away the need for the errant but practically useful Ptolemaic models. Finally, the patient observations of the Italian astronomer and physicist Galileo, in particular his observations of moons circling Jupiter and of the phases of Venus, empirically laid to rest cosmologies that placed Earth at the center of the Cosmos.

English physicist and mathematician Sir Isaac Newton's (1642–1727), important *Philosophiae Naturalis Principia Mathematica* (Mathematical principles of natural philosophy) quantified the laws of motion and **gravity** and thereby enabled cosmologists to envision a clockwork-like universe governed by knowable and testable natural laws. Within a century of Newton's *Principia,* the rise of concept of a mechanistic universe led to the quantification of celestial dynamics, that, in turn, led to a dramatic increase in the observation, cataloging, and quantification of celestial phenomena. In accordance with the development of natural theology, scientists and philosophers debated conflicting cosmologies that argued the existence and need for a supernatural God who acted as "prime mover" and guiding force behind a clockwork universe. In particular, French mathematician Pierre Simon de Laplace (1749–1827) argued for a completely deterministic universe, without a need for the intervention of God. Most importantly to the development of modern cosmology, Laplace asserted explanations for celestial phenomena as the inevitable result of time and statistical probability.

By the dawn of the twentieth century, advances in mathematics allowed the development of increasingly sophisticated cosmological models. Many advances in mathematics pointed toward a universe not necessarily limited to three dimensions and not necessarily absolute in time. These intriguing ideas found expression in the intricacies of relativity and theory that, for the first time, allowed cosmologists a theoretical framework upon which they could attempt to explain the innermost workings and structure of the universe both on the scale of the subatomic world and on the grandest of galactic scales.

As direct consequence of German-American physicist Albert Einstein's (1879–1955) **relativity theory**, cosmologists advanced the concept that space-time was a creation of the universe itself. This insight set the stage for the development of modern cosmological theory and provided insight into the evolutionary stages of stars (e.g., neutron stars, pulsars, black holes, etc.) that carried with it an understanding of nucleosythesis (the formation of elements) that forever linked the physical composition of matter on Earth to the lives of the stars.

Twentieth-century progress in cosmology has been marked by corresponding and mutually beneficial advances in technology and theory. American astronomer Edwin Hubble's (1889–1953) discovery that the universe is expanding, Arno A. Penzias and Robert W. Wilson's observation of cosmic background radiation, and the detection of the elementary particles that populated the very early universe all proved important confirmations of the **Big Bang theory**. The Big Bang theory asserts that all matter and energy in the universe, and the four dimensions of time and **space** were created from the primordial explosion of a singularity of enormous density, **temperature**, and pressure.

During the 1940s Russian-born American cosmologist and nuclear physicist George Gamow (1904–1968) developed the modern version of the big bang model based upon earlier concepts advanced by Russian physicist Alexander (Aleksandr Aleksandrovich) Friedmann (also spelled as Fridman, 1888–1925) and Belgian astrophysicist and cosmologist Abbé Georges Lemaître (1894–1966). Big bang based models replaced static models of the universe that described a homogeneous universe that was the same in all directions (when averaged over a large span of space) and at all times. Big bang and static cosmological models competed with each other for scientific and philosophical favor. Although many astrophysicists rejected the steady state model because it would violate the law of mass-energy conservation, the model had many eloquent and capable defenders. Moreover, the steady model was interpreted by many to be more compatible with many philosophical, social and religious concepts centered on the concept of an unchanging universe. The discovery of **quasars** and of a permeating cosmic background radiation eventually tilted the cosmological argument in favor of big bang-based models.

Technology continues to expand the frontiers of cosmology. The **Hubble Space Telescope** has revealed gas **clouds** in the cosmic voids and beautiful images of fledgling galaxies formed when the universe was less than a billion years old. Analysis of these pictures and advances in the understanding of the fundamental constituents of nature continue to keep cosmology a dynamic discipline of **physics** and the ultimate fusion of human scientific knowledge and philosophy.

See also Cosmic microwave background radiation; Stellar life cycle

COUNTRY ROCK

The term country **rock** refers to a body of rock that receives or hosts an intrusion of a viscous geologic material. Intrusions into country rock are most commonly magmatic, but may also consist of unconsolidated sediments or salt horizons. Country rock may consist any other kind of rock that was present before the intrusion: sedimentary, igneous, or metamorphic.

In most cases, country rock is intruded by an igneous body of rock that formed when **magma** was forced upward through fractures or melted its way up through the overlying rock. The magma then cooled into solid rock forming a mass distinct from the enveloping country rock. Occasionally, a fragment of country rock will break off and become incorporated into the intrusion, and is called a **xenolith**.

The country rock is usually altered by the heat of the intrusion. The change that takes place in country rock as a result of an intrusion cooling off is called contact **metamorphism**. The extent and intensity of contact metamorphism depends on the heat of the magma, the **temperature** of the country rock, the amount of fluids present, the **permeability** of the country rock, and the depth of intrusion (which determines to a great extent, the pressure). The metamorphism is strongest at the contact of the country rock and the intrusion and diminishes outward from the intrusion. A discernable halo of contact metamorphism that extends into the country rock is often produced and is called the contact aureole.

When the country rock has been contact metamorphosed, it often experiences mineralogical alterations that result in a rock quite different from the original. One common rock type produced by contact metamorphism is called **hornfels**. It is a very fine-grained rock with little recognizable texture. Another is called skarn, a rock rich in calc-silicate **minerals** and often the product of a **limestone** or **dolomite** country rock.

The other, less common form of intrusion into country rock consists of geologic material that is able to flow, but is not molten rock. This material can be unconsolidated sediment that has sufficient **water** content to act as a fluid. These are termed soft sediments and if there is sufficient pressure from the overlying rocks, they can be forced into fractures into country rock. The resulting intrusion is called a diatreme. Another type of material that forms diatremes is salt. Salt has a lower density than most other rocks and when buried, salt horizons can become viscous and will flow upward. In both soft sediment intrusions and salt diatremes, the county rock is not metamorphosed. However, diatremes do disrupt the country rock, sometimes producing visible bulges.

See also Intrusive cooling

COUSTEAU, JACQUES-YVES (1910-1997)

French oceanographer

Jacques Cousteau was known as the co-inventor of the aqualung, along with his television programs, feature-length films, and books, all of which have showcased his research on the wonders of the marine world. Cousteau helped demystify undersea life, documenting its remarkable variety, its interdependence, and its fragility. Through the Cousteau Society, which he founded, Cousteau led efforts to call attention to environmental problems and to reduce marine pollution.

Jacques-Yves Cousteau was born in St. André-de-Cubzac, France, on June 11, 1910 to Elizabeth Duranthon and Daniel Cousteau. Jacques, for the first seven years of his life, suffered from chronic enteritis, a painful intestinal condition. In 1918, after the Treaty of Versailles, Daniel found work as legal adviser to Eugene Higgins, a wealthy New York expatriate. Higgins traveled extensively throughout **Europe**, with the Cousteau family in tow. Cousteau recorded few memories from his childhood; his earliest impressions, however, involved **water** and ships. His health greatly improved around this time, thanks in part to Higgins, who encouraged young Cousteau to learn how to swim.

In 1920, the Cousteaus accompanied Higgins to New York City. Here, Jacques attended Holy Name School in Manhattan, learning the intricacies of stickball and roller-skating. He spent his summers at a camp on Vermont's Lake Harvey, where he first learned to dive underwater. At age 13, after a trip south of the American border, he authored a handbound book he called "An Adventure in Mexico." That same year, he purchased a Pathé movie camera, filmed his cousin's marriage, and began making short melodramatic films.

During his teens, Cousteau was expelled from a French high school for "experimenting" on the school's windows with different-sized stones. As punishment, he was sent to a military-style academy near the French-German border, where he became a dedicated student. He graduated in 1929, unsure of which career path to follow. The military won out over filmmaking simply because it offered the opportunity for extended travel. After passing a rigorous entrance examination, he was accepted by the Ecole Navale, the French naval academy. His class embarked on a one-year world cruise, which he documented, filming everything and everyone—from Douglas Fairbanks, the famous actor, to the Sultan of Oman. After graduating second in his class in 1933, he was promoted to second lieutenant and sent to a naval base in Shanghai, China. His assigned duty was to survey and map the countryside, but in his free time he filmed the locals in China and Siberia.

In the mid–1930s, Cousteau returned to France and entered the aviation academy. Shortly before graduation, in 1936, he was involved in a near-fatal automobile accident that mangled his left forearm. His doctors recommended amputation but he steadfastly refused. Instead, he chose rehabilitation, using a regimen of his own design. He began taking daily swims around Le Mourillon Bay to rehabilitate his injured arm. He fell in love with goggle diving, marveling at the variety and beauty of undersea life. He later wrote in his book *The Silent World*: "One Sunday morning...I waded into the Mediterranean and looked into it through Fernez goggles...I was astonished by what I saw in the shallow shingle at Le Mourillon, rocks covered with green, brown and silver **forests** of algae and fishes unknown to me, swimming in crystalline water...Sometimes we are lucky enough to know that our lives have been changed, to discard the old, embrace the new, and run headlong down an immutable course. It happened to me at Le Mourillon on that summer's day, when my eyes were opened on the sea."

During his convalescence he met 17-year-old Simone Melchior, a wealthy high-school student who was living in Paris. After a one-year courtship, the couple married and moved into a house near Le Mourillon Bay. The Cousteaus' first son, Jean-Michel, was born in March of 1938. A second son, Philippe, was born in 1939. Around this time, the new family's tranquil life on the edge of the sea was threatened by world events. In 1939, France began preparing for war, and Cousteau was promoted to gunnery officer aboard the *Dupleix*. The war was largely limited to ground action, however, and Germany quickly overran the ill-prepared French Army. Living in the unoccupied section of France enabled Cousteau to continue his experiments and allowed him to spend many hours with his family. In his free time, he experimented with underwater photography devices and tried to develop improved diving apparatuses. German patrols often questioned Cousteau about his use of diving and photographic equipment. Although he was able to convince authorities that the equipment was harmless, Cousteau was, in fact, using these devices on behalf of the French resistance movement. For his efforts, he was later awarded the Croix de Guerre with palm.

Cousteau regretted the limitations of goggle diving; he simply could not spend enough time under water. The standard helmet and heavy suit apparatus had similar limitations; the diver was helplessly tethered to the ship, and the heavy suit and helmet made Cousteau feel awkward in his movements. A number of experiments with other diving equipment followed, but all the existing systems proved unsatisfactory. He designed his own "oxygen re-breathing outfit," which was less physically constrictive but which ultimately proved ineffective and dangerous. Also during this period he began his initial experiments with underwater filmmaking. Working with two colleagues, Philippe Talliez, a naval officer, and Frédéric Dumas, a renowned spearfisherman, Cousteau filmed his first underwater movie, *Sixty Feet Down*, in 1942. The 18-minute film reflects the technical limitations of underwater photography but was quite advanced for its time. Cousteau entered the film in the Cannes Film Festival, where it received critical praise and was purchased by a film distributor.

As pleased as he was with his initial efforts at underwater photography, Cousteau realized that he needed to spend more time underwater to accurately portray the ocean's mysteries. In 1937, he began collaboration with Emile Gagnan, an engineer with a talent for solving technical problems. In 1942, Cousteau again turned to Gagnan for answers. The two spent approximately three weeks developing an automatic regulator that supplied compressed air on demand. This regulator, along with two tanks of compressed air, a mouthpiece, and hoses, was the prototype Aqualung, which Gagnan and Cousteau patented in 1943.

That summer, Cousteau, Talliez, and Dumas tested the Aqualung off the French Riveria, making as many as five hundred separate dives. This device was put to use on the group's next project, an exploration of the *Dalton*, a sunken British steamer. This expedition provided material for Cousteau's second movie, *Wreck*. The film deeply impressed French naval authorities, who recruited Cousteau to assist with the dangerous task of clearing mines from French harbors. When the war ended, Cousteau received a commission to continue his research as part of the Underwater Research Group, which included both Talliez and Dumas. With increased funding and ready access to scientists and engineers, the group expanded its research and developed a number of innovations, including an underwater sled.

In 1947, Cousteau, using the Aqualung, set a world's record for free diving, reaching a depth of 300 feet. The following year, Dumas broke the record with a 306-foot dive. The team developed and perfected many of the techniques of deep-sea diving, working out rigorous decompression schedules that enabled the body to adjust to pressure changes. This physically demanding, dangerous work took its toll; one member of the research team was killed during underwater testing.

On July 19, 1950, Cousteau bought *Calypso*, a converted U.S. minesweeper. The next year, after undergoing significant renovations, *Calypso* sailed for the Red Sea. The *Calypso* Red Sea Expedition (1951–52) yielded numerous discoveries, including the identification of previously unknown plant and animal species and the discovery of volcanic basins beneath the Red Sea. In February of 1952, *Calypso* sailed toward Toulon. On the way home, the crew investigated an uncharted wreck near the southern coast of Grand Congloué and discovered a large Roman ship filled with treasures. The discovery helped spread Cousteau's fame in France. In 1953, with the publication of *The Silent World*, Cousteau achieved international notice. The book, drawn from Cousteau's daily logs, was written originally in English with the help of U.S. journalist James Dugan and later translated into French. Released in more than 20 languages, *The Silent World* eventually sold more than five million copies worldwide.

In 1953, Cousteau began collaborating with Harold Edgerton, a pioneer in high-speed photography who had invented the strobe light and other photographic devices. Edgerton and his son, William, spent several summers aboard *Calypso*, outfitting the ship with an innovative camera that skimmed along the ocean floor, sending back blurry but intriguing photos of deep-sea creatures. The death of William Edgerton in an unrelated diving accident effectively ended the experiments, but Cousteau had already realized the limitations of such a method of exploring the ocean depths. Instead, he and his team began work on a small, easily maneuverable submarine, which he called the diving saucer, or DS–2. The sub has made more than one thousand dives and has been part of countless undersea discoveries.

In 1955, *Calypso* embarked on a 13,800-mile journey that was recorded by Cousteau for a film version of *The Silent World*. The ninety-minute film premiered at the 1956 Cannes International Film Festival, where it received the coveted Palme d'Or. The following year, the film won an Oscar from the American Academy of Motion Picture Arts and Sciences. In 1957, in part due to his film's success, Cousteau was named director of the Oceanographic Institute and Museum of Monaco. He filled the museum's aquariums with rare and unusual species garnered from his ocean expeditions.

Cousteau addressed the first World Oceanic Congress in 1959, an event that received widespread coverage and led to his appearance on the cover of *Time* magazine on March 28, 1960. The highly favorable story painted Cousteau as a poet of the deep. In April of 1961, Cousteau received the National Geographic Society's Gold Medal at a White house ceremony hosted by President John F. Kennedy. The medal's inscription reads: "To earthbound man he gave the key to the silent world."

During the early 1960s, Cousteau and his crew participated in the Conshelf Saturation Dive program, which was intended to prove the feasibility of extended underwater living. The success of the first mission led to Conshelf II, a month-long project involving five divers. The Conshelf program and the DS–2 project provided material for the 53-minute film *World without Sun*, which debuted in the United States in December of 1964.

Cousteau's first hour-long television special, "The World of Jacques-Yves Cousteau," was broadcast in 1966. The program's high ratings and critical acclaim helped Cousteau land a lucrative contract with the American Broadcasting Company (ABC). The *Undersea World of Jacques Cousteau* premiered in 1968, and has since been rebroadcast in hundreds of countries. The program starred Cousteau and his sons, Philippe and Jean-Michel. The show ran for eight **seasons**, with the last episode airing in May of 1976. In 1977, the *Cousteau Odyssey* series premiered on the Public Broadcasting System. The new show reflected Cousteau's growing concern about environmental destruction and tended not to focus on specific animal species.

In the 1970s, the Cousteau Society, a nonprofit environmental group that also focuses on peace issues, opened its doors in Bridgeport, Connecticut. By 1975, the society had more than 120,000 members and had opened branch offices in Los Angeles, New York, and Norfolk, Virginia. Eventually, Cousteau decided to make Norfolk the home base for *Calypso*.

On June 28, 1979, Philippe Cousteau was killed when the seaplane he was piloting crashed on the Tagus River near Lisbon, Portugal. Philippe's death deeply affected Cousteau, who was to his death unable to talk about the accident or the loss of his son. Philippe was expected to eventually take command of his father's empire; instead, Jean-Michel was given increased responsibility for overseeing the Cousteau Society and his father's other ventures.

In 1980, Cousteau signed a one-million-dollar contract with the National Office of Canadian Film to produce two programs on the greater St. Lawrence waterway. In 1984, the *Cousteau Amazon* series premiered on the Turner Broadcasting System. The four shows were enthusiastically reviewed, and called attention to the threatened native South American cultures, Amazon rain forest, and creatures that lived in one of the world's great **rivers**. The final show of the series, "Snowstorm in the Jungle," explored the frightening world of cocaine trafficking. In the mid–1980s "Cousteau/Mississippi: The Reluctant Ally" received an Emmy award for outstanding informational special. In all, Cousteau's television programs have earned more than 40 Emmy nominations.

In addition to his television programs, Cousteau continued to produce new inventions. The Sea Spider, a many-armed diagnostic device, was developed to analyze the biochemistry of the ocean's surface. In 1980, Cousteau and his team began work on the Turbosail, which uses high-tech **wind** sails to cut fuel consumption in large, ocean-going vessels. In spring of 1985, he launched a new wind ship, the *Alcyone*, which was outfitted with two 33-foot-high Turbosails.

In honor of his achievements, Cousteau received the Grand Croix dans l'Ordre National du Mérite from the French government in 1985. That same year, he also received the U.S. Presidential Medal of Freedom. In November of 1987, he was inducted into the Television Academy's Hall of Fame and later received the founder's award from the International Council of the National Academy of Television Arts and Sciences. In 1988, the National Geographic Society honored him with its Centennial Award for "special contributions to mankind throughout the years."

While some critics challenged his scientific credentials, Cousteau never claimed "expert" status in any discipline. His talents appeared as poetic as scientific; his films and books—which include the eight-volume *Undersea Discovery* series and the 21-volume *Ocean World* encyclopedia series—have a lyrical quality that conveys the captain's great love of nature. This optimism was tempered by his concerns about the environment. He emphatically demonstrated, perhaps to a greater degree than any of his contemporaries, how the quality of both the land and sea is deteriorating and how such environmental destruction is irreversible.

Cousteau continued to speak publicly about environmental issues until he was well into his eighties, although he had given up diving in cold water. In the years before his death, he had been planning for the construction of the *Calypso 2* to replace the original *Calypso*, which had sunk in a Singapore shipyard in 1994. The $20 million vessel was to be powered by **solar energy** and include equipment for a television studio, marine laboratory, and **satellite** transmission facility. The oceanographer died of a heart attack in 1997, at his home in Paris, after suffering from a respiratory ailment. He was 87.

COVALENT BONDS • *see* CHEMICAL BONDS AND PHYSICAL PROPERTIES

CRATER, VOLCANIC

A crater is a steep-sided roughly circular to elliptical depression in the earth caused either by volcanic activity or by the impact of an extraterrestrial body. Volcanic craters are formed by explosive events, and/or by the collapse of part of a **volcano** following withdrawal of **magma**. Impact craters are the result of collisions between Earth and extraterrestrial bodies such as meteors or **comets**.

Large volcanic craters are known as calderas among vulcanologists. There are two often-complementary processes involved in their formation; violent eruptions of ash and magma, and/or the collapse of a volcanic surface following withdrawal of a large body of magma from the subsurface. An example of the first type may be Crater Lake in Oregon, thought to have been produced by a violent explosion that destroyed a volcano the size of Mount St. Helens. The **caldera** at Kilauea, in contrast, is thought to be the result of magma drainage from beneath the summit. There is still significant discussion about whether volcanic calderas are formed directly by explosion, indirectly by collapse of the surface following magma ejection or withdrawal, or by both.

Impact craters are the result of collisions of extraterrestrial bodies with the earth. Only recently have scientists begun to understand the importance of impact processes in shaping the planet and life on it. Exploration of our **solar system** has revealed that essentially all planetary bodies are cratered. The density of craters on the older surfaces of the **Moon** indicates an intense bombardment from approximately 4.6 to 3.9 billion years ago. The Moon itself is likely the result of a collision of a Mars size object with a young Earth. The earth experienced the same bombardment as the other planetary bodies. In fact, Earth is subject to about twice as many impacts as the moon because of the difference in **gravity**. This is not obvious because tectonic and **erosion** activity on the earth have removed evidence of most of the impacts that have occurred. Nevertheless, approximately 150 craters have been identified, with more recognized every year.

Perhaps the most well-known **impact crater** on Earth is Chicxulub, a buried crater in the Yucatan, Mexico, that is 110 miles (180 kilometers) in diameter. Most geoscientists now believe that this impact event was responsible for the great mass extinction of the dinosaurs and many other species at the Cretaceous/Tertiary (K-T) boundary, 65 million years ago. Impacts this size occur infrequently, on the order of one every 100 million years. However, impacts that could cause damage similar to a **nuclear winter**, occur at time scales estimated as two or three every million years. This estimate is significant because the most recent known event, Zhamanshin in Kazaksthan, occurred about a million years ago.

See also Meteoroids and meteorites; Volcanic eruptions

CRATON

Cratons are large regions of continental **crust** that have remained tectonically stable for a prolonged period of time, often a billion years or more. **Precambrian** cratons are commonly cored by Archaean granite-greenstone terrains and may be partly covered by sedimentary platform sequences. The North American Craton, Laurentia, which constitutes much of **North America**, formed by the assembly of smaller cratons in the **Archean** and Paleoproterozoic. Cratons are surrounded by orogenic (mountain building) or mobile belts, within which deformation has been localized. For example, cratons comprised of Archean granite-greenstone terrains and Paleoproterozoic sedimentary sequences in **Africa**, central India and Western **Australia** are rimmed by Mesoproterozoic and Neoproterozoic orogenic belts, many of which have been subsequently reactivated during **rifting** and the formation of Paleozoic sedimentary basins. Only minor reactivation of older structural weaknesses occurs in craton interiors during deformation on their margins.

Cratons have thick lithospheric roots or keels. Lithospheric thicknesses for Archean cratons show a bimodal distribution, with thicknesses of approximately 137 mi (220 km) and 218 mi (350 km) predominating. Larger cratons generally have thicker lithospheres. In contrast, post-Archean **lithosphere** is generally 62–124 mi (100–200 km) thick. The physical and/or chemical properties of the deep roots of cratons enable them to resist recycling into the underlying asthenopsheric mantle. This may be responsible for the stability of cratons. Isotopic signatures obtained from mantle lithosphere-derived, **peridotite** xenoliths and inclusions in diamonds imply that roots to Precambrian cratons have been isolated from the convecting mantle for billions of years. Archean subcontinental lithospheric mantle is buoyant relative to the underlying **asthenosphere**. It is therefore not easily delaminated and assimilated into the asthenosphere and will tend to be preserved. Geochemical changes may also impart stability to cratonic roots. **Mantle plumes** are generally unable to break and induce rifting of thick, cratonic lithosphere and may be deflected around cratons. Despite their buoyancy, the margins of cratons can be deformed at subduction zones, however, due to the development of detachments at the interface between crust and mantle lithospheric root. Numerical modeling suggests that the dominant stabilizing factor for the preservation of cratons is the relatively high brittle yield stress of cratonic lithosphere. As the strength of the continental lithosphere resides primarily within the crust, the physical properties of the crust may also play a role in the longevity of cratonic lithosphere.

Favorable pressures and temperatures for the formation and preservation of **diamond** are found beneath cratons. Diamond crystallizes from liquid **carbon** between 1652°–2192°F (900–1200°C) at pressures above 50 kbar. At this pressure, equating to a depth of 93 mi (150 km) or more, temperatures are generally too high for the formation of diamond except in the roots beneath cratons. Most of the world’s diamonds come from deep, mantle-sourced intrusive bodies such as kimberlites or lamproites that intrude Archaean cratons. Kimberlite and lamproite magmas intrude extremely rapidly up deep fractures and may bring diamonds to shallow levels in the crust. Near the earth’s surface, they erupt explosively due to their high gas pressures, creating **breccia** pipes (called diatremes) and craters.

See also Plate tectonics

CREEP

The slow, often imperceptible downslope movement of **soil** or other debris is called creep. Because creep moves materials so slowly, it is difficult to discern directly. Observation of the effects of creep, such as bent trees, tilted fences, and cracked walls, usually leads to identification of the problem.

Creep is caused by the interaction of multiple factors, but heaving is likely the most important process. Heaving involves the expansion and contraction of **rock** fragments, and occurs during cycles of wetting and drying, as well as **freezing** and thawing. As expansion occurs, particles move outward, perpendicular to the hillside. During contraction, the particles move back toward the hillside, vertically, and end up slightly downslope of where they began. The repeated motion of individual particles results in net downslope movement of the material. Areas that undergo wet/dry or freeze/thaw cycles are most susceptible to creep.

Solifluction is a special type of creep that occurs in cold regions underlain by **permafrost**. During the winter, the ground freezes right up to the surface. When the surface layer thaws, during the spring and early summer, the meltwater cannot percolate downward into the frozen layers beneath. This causes the surface layer of soil to become waterlogged, facilitating downslope movement as the layer becomes saturated. In this case the surface layer flows, riding above the frozen ground beneath. Although most common in permafrost areas, solifluction can occur anywhere that the surface soil layer becomes saturated.

Although movement associated with creep is slow, it causes significant economic damage because it is a widespread phenomenon that is probably occurring to some extent on virtually all soil-covered slopes. Some of the problem relates to the difficulty of detection. Unless trees, walls, or other built structures are deformed, it is difficult to impossible to determine whether or not creep is occurring. Unfortunately, where creep has been identified, it is also difficult to control. The best response to the problem is to avoid building in areas undergoing creep. Where construction is necessary, buildings should be anchored to **bedrock** beneath the creeping soil and debris layer.

See also Mass wasting; Regolith; Weathering and weathering series

CRETACEOUS PERIOD

Cretaceous is the name given to a period of time in Earth's history (i.e., Cretaceous Period) from 145.6 to 65 million years ago. Also, all the rocks that formed during that time have the same proper name of Cretaceous (i.e., they are referred to as the Cretaceous System). Said differently, the Cretaceous System is the **rock** record of events that occurred—and organisms that lived—during a span of geological time that is called Cretaceous Period. Cretaceous was the third and final period of the **Mesozoic Era**.

Cretaceous is a name derived from the Latin word for chalk, *creta*. Chalk is a common type of sedimentary rock formed during this interval of Earth history. The term Cretaceous was first used in 1822 by d'Omalius d'Halloy (1707–1789), a Belgian geologist who was engaged in pioneering efforts at geological mapping of parts of France. He mapped the *Terrain Cretac* (Cretaceous System) within the Paris Basin and later in Belgium. D'Halloy's strata were easily correlated with chalks mapped earlier, but not formally named, by **William Smith** (1769–1839) on his revolutionary 1815 geological map. Other geologists of the day rapidly correlated the Cretaceous System with chalks they found in northern France, Holland, Denmark, northern Germany, Poland, and Sweden. Since their recognition and definition during the nineteenth century, Cretaceous strata have been mapped on all the world's continents.

During Cretaceous, the breakup of the supercontinent of Pangaea became nearly complete. The Atlantic Ocean opened sufficiently so that a substantial body of **water** existed between **North America** and **Europe** and **South America** and **Africa** were widely separated. While the Atlantic was opening, the Pacific Ocean continued to close rapidly and an episode of major tectonic change occurred as a result in western North and South America. Specifically, a major **subduction zone** developed along the western coast of the Americas and substantial tectonic uplift and volcanic activity occurred along this western margin.

During most of Cretaceous, global sea levels were at some of their highest elevations in the last 500 million years of Earth history. Much of the low-lying areas of the world's continents were covered by shallow **seas**, also known as epicontinental seas. During part of Late Cretaceous, sea level was so high (approximately 275 m above present level) that an epicontinental sea (i.e., Western Interior Seaway) connected the **Gulf of Mexico** with the Arctic Ocean through the center of North America. (The Rocky Mountains were not formed at this time, and thus this **area** was rather low-lying and flat).

Cretaceous was a time of elevated global temperatures and there were essentially no polar or high-altitude **glaciers**. This contributed to elevated sea levels as did the vast development of volcanic activity along Earth's **mid-ocean ridges**. Such volcanic activity and accompanying swelling of these undersea ridges displaced a considerable volume of seawater (strongly exacerbating sea-level rise). Also, there was rapid **sea-floor spreading** during Cretaceous. Further, effusive volcanism from mantle hot spots caused flood basalts to erupt on land, the most noteworthy of these produced the massive Deccan Traps of India.

Cretaceous life in the **oceans** was very plentiful, with numerous species of fish, sharks, rays, ammonites, turtles, mosasaurs, plesiosaurs, and other creatures plying ocean waters. Numerous massive reef systems developed, including one rimming the Gulf of Mexico during Early Cretaceous, which was dominated by a specialized type of large clams called rudists. Large oysters were common at this time. The main plankon, the golden-brown alga, produced massive amounts of calcareous platelets that settled to the sea floor along with abundant foraminifers thus forming an ooze that eventually became the famous Cretaceous chalk (as seen at the White Cliffs of Dover, England, and many other areas).

Cretaceous life on land was dominated by the reptiles, which dwelt for the most part in heavily vegetated terrains. Lush Cretaceous cycad-ginko-conifer **forests** and swamps are well preserved in vast tracts of **coal** and lignite deposits of this age. Late Cretaceous was the time of development of flowing plants and co-evolution of a very diverse insect population. Land animals such as snakes, lizards, crocodiles, dinosaurs, pterosaurs, birds, and small mammals were common. Among the dinosaurs, Cretaceous ecosystems saw the rise of many diverse types, which were indigenous to the rapidly separating continental land masses. The rising groups of dinosaurs during this time included pachycephalosarus, ceratopsians, iguanodonts, hadrosaurs, coelurosaurs, and carnosaurs (e.g., tyrannosaurids).

The end of Cretaceous came abruptly with global ecosystem collapse and mass extinction. The end-Cretaceous catastrophe resulted in rapid death of nearly 50% of all living species of organisms. Known since the nineteenth century as an inexplicable sudden mass death marker, the Cretaceous-Tertiary (K-T) boundary has attracted considerable interest from researchers in recent years because the boundary **clay** layer contains a substantial enrichment in certain **chemical elements** (e.g., iridium), which are much more common in **asteroids** and **comets** than on Earth. Discovery in the 1980s of a 180-km diameter **impact crater** in the state of Yucatan, Mexico, which has the same age as the K-T boundary, indicates a strong connection between the mass death and cosmic impact at this time in Earth history. Subsequent studies have shown that impact of a 10-km diameter asteroid at Yucatan could have resulted in such a global ecosystem collapse and accompanying mass death. The impact crater is known as Chicxulub, which is a Mayan word meaning “tail of the Devil.”

See also Chronostratigraphy; K-T event; Impact crater; Mesozoic Era; Stratigraphy; Supercontinents

CRETACEOUS-TERTIARY MASS EXTINCTION EVENT • *see* K-T EVENT

CROSS BEDDING • *see* BEDDING

CROSS CUTTING

Cross-cutting relationships among geological features have been recognized for many years as one of the fundamental ways of determining relative age relationships between adjacent geological features. The principle of cross-cutting relationships, explained by **James Hutton** (1726–1797) in *Theory of the Earth* (1795) and embellished upon by **Charles Lyell** (1797–1875) in his *Principles of Geology* (1830), holds that the geological feature which cuts another is the younger of the two features. For example, in the instance of an igneous **dike** cutting through a layer of **sandstone**, the dike must be younger than the sandstone.

Cross-cutting relationships are of several basic types. There are structural cross-cutting relationships wherein a fault or fracture cuts through older **rock**. Stratigraphic cross-cutting relationships occur where an erosional surface (or unconformity) cuts across older rock layers, geological structures, or other geological features. Sedimentologic cross-cutting relationships occur where currents have eroded or scoured older sediment in a local **area** to produce, for example, a channel filled with **sand**. Paleontologic cross-cutting relationships occur where animal activity or plant growth produce truncation. This happens, for example, where animal burrows penetrate into pre-existing sedimentary deposits. Geomorphic cross-cutting relationships occur where a surficial feature, such as a river, flows through a gap in a ridge of rock. In a similar example, an **impact crater** excavates into a subsurface layer of rock.

Cross-cutting relationships may be seen cartographically, megascopically, and microscopically. In other words, these relationships have various scales. A cartographic cross-cutting relationship might look like, for example, a large fault dissecting the landscape on a large map. Megascopic cross-cutting relationships are features like igneous dikes, as mentioned above, which would be seen on an outcrop or in a limited geographic area. Microscopic cross-cutting relationships are those that require study by magnification or other close scrutiny. For example, penetration of a fossil shell by the drilling action of a boring organism is an example of such a relationship.

Cross-cutting relationships may be compound in nature. For example, if a fault were truncated by an unconformity, and that unconformity cut by a dike, we can say, based upon compound cross-cutting relationships that the fault is older than the unconformity and that the unconformity is older than the dike. Using such rationale, the sequence of geological events can be better understood.

Cross-cutting relationships can also be used in conjunction with radiometric age dating to effect an age bracket for geological materials that cannot be directly dated by radiometric techniques. For example, if a layer of sediment containing a fossil of interest is bounded on the top and bottom by **unconformities**, where the lower unconformity truncates dike A and the upper unconformity truncates dike B (which penetrates the layer in question), this method can be used. A radiometric age date from **crystals** in dike A will give the maximum age date for the layer in question and likewise, crystals from dike B will give us the minimum age date. This provides an age bracket, or range of possible ages, for the layer in question.

The principle of cross-cutting relationships, like the principles of **superposition** and inclusions, is one of the most basic tools used by geologists to understand relative age relationships on Earth and on planetary and **satellite** surfaces in our **solar system**.

CRUST

Earth’s mass is divided into an inner core, outer core, mantle, and crust. The crust is outermost layer of the earth, 3–44 miles (5–70 km) thick and representing less than 1% of the earth’s total volume. Thin compared Earth’s diameter, the outermost crustal layer is further subdivided into two basic types of crust—each unique in composition, origin and fate. Although the earth is dynamic, with new crust constantly being created and destroyed, the fact that size of the earth remains constant argues that there is no net creation or destruction of force and that these two processes are in equilibrium.

Although there are thousands of **minerals**, about 40 minerals represent more than 99% of the mass of Earth's crust. In terms of percentage of Earth's crust by weight, **oxygen** and **silicon** account for nearly 75% of Earth's crust. Oxygen is the most abundant element (approximately 46.5% followed by silicon, approximately 28%). In order of percentage by weight, other important elements include **aluminum**, **iron**, calcium, sodium, potassium, and magnesium. All other elements (e.g., gold, silver, copper, etc.) compose the remaining one to two percent of the crust.

Crust is classified as oceanic crust or continental crust.

Oceanic crust is thin (3–4.3 mi [5–7 km]), basaltic ($<$50% SiO_2) and dense. Compositional chemical studies also establish that oceanic crust is substantially younger than the continental crust. No **rock** specimen dated to more than 250 million years old have ever been identified in oceanic crust.

Continental crust is thick (18.6–40 mi [30–65 km]), granitic ($>$60% SiO_2), light, and old (250–3,700 million years old).

The outer crust is further subdivided into **lithospheric plates**, that contain varying sections of oceanic and continental crust.

At the deepest crustal border there exists a compositional change from crust material to mantle pyriditite called the **Mohorovicic discontinuity**, and the lithospheric plates carrying both oceanic and continental crust move on top of mantle's **asthenosphere**.

See also Dating methods; Earth, interior structure; Geologic time; Hawaiian Island formation; Isostasy; Lithospheric plates; Mid-ocean ridges and rifts; Mohorovicic discontinuity (Moho); Ocean trenches; Plate tectonics; Rifting and rift valleys; Soil and soil horizons; Subduction zone

CRUTZEN, PAUL J. (1933-)

Dutch meteorologist

Paul Crutzen is one of the world's leading researchers in mapping the chemical mechanisms that affect the ozone layer. He has pioneered research on the formation and depletion of the **ozone** layer and the potential threats placed upon it by industrial society. Crutzen has discovered, for example, that nitrogen oxides accelerate the rate of ozone depletion. He has also found that chemicals released by bacteria in the **soil** affect the thickness of the ozone layer. For these discoveries, he has received the 1995 Nobel Prize in Chemistry, along with **Mario Molina** and Sherwood Rowland for their separate discoveries related to ozone and how chlorofluorocarbons (CFCs) deplete the ozone layer. According to Royal Swedish Academy of Science, "by explaining the chemical mechanisms that affect the thickness of the ozone layer, the three researchers have contributed to our salvation from a global environmental problem that could have catastrophic consequences."

Paul Josef Crutzen was born December 3, 1933, to Josef C. Crutzen and Anna Gurek in Amsterdam. Despite growing up in a poor family in Nazi-occupied Holland during 1940–1945, he was nominated to attend high school at a time when not all children were accepted into high school. He liked to play soccer in the warm months and **ice** skate 50–60 miles (80–97 km) a day in the winter. Because he was unable to afford an education at a university, he attended a two-year college in Amsterdam. After graduating with a civil engineering degree in 1954, he designed bridges and homes.

Crutzen met his wife, Tertu Soininen, while on vacation in Switzerland in 1954. They later moved to Sweden where he worked as a computer programmer for the Institute of **Meteorology** and the University of Stockholm. He started to focus on **atmospheric chemistry** rather than mathematics because he had lost interest in math and did not want to spend long hours in a lab, especially after the birth of his two daughters. Despite his busy schedule, Crutzen obtained his doctoral degree in Meteorology at Stockholm University at the age of 35.

Crutzen's main research focused on ozone, a bluish, irritating gas with a strong odor. Ozone is a molecule made up of three **oxygen** atoms (O_3) and is formed naturally in the atmosphere by a photochemical reaction. The ozone layer begins approximately 10 miles (16 km) above Earth's surface, reaching 20–30 miles (32–48 km) in height, and acts as a protective layer that absorbs high-energy ultraviolet radiation given off by the **sun**.

In 1970, Crutzen found that soil microbes were excreting nitrous oxide gas, which rises to the **stratosphere** and is converted by sunlight to nitric oxide and nitrogen dioxide. He determined that these two gases were part of what caused the depletion of the ozone. This discovery revolutionized the study of ozone and encouraged a surge of research on global **biogeochemical cycles**.

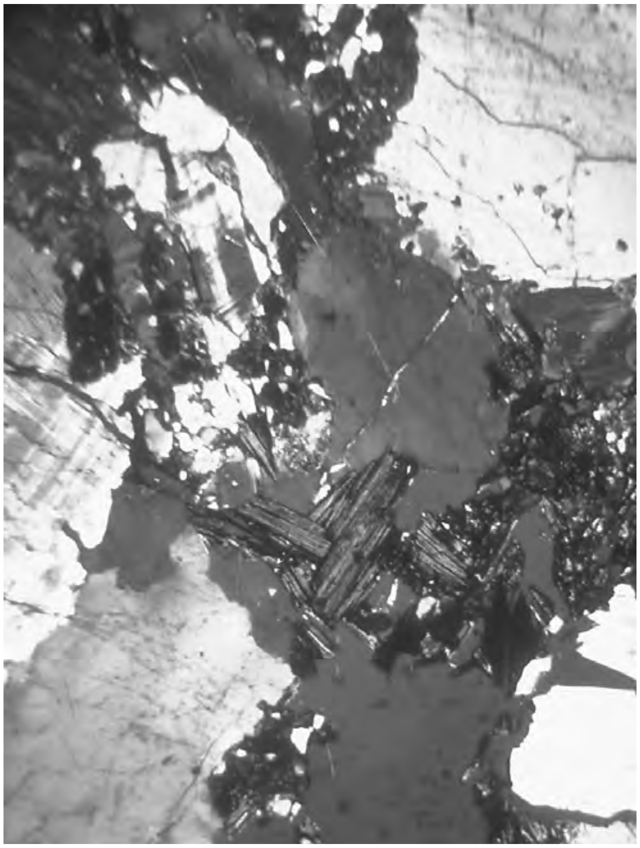
In 1977, while he was the director of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, Crutzen studied the effects of the mass burning of trees and brush in the fields of Brazil. The theory at the time was that this burning caused more **carbon** compounds—trace gases and carbon monoxide—to enter the atmosphere. These gases were assumed to cause the **greenhouse effect**, or a warming of the atmosphere. Crutzen collected and examined this smoke in Brazil and discovered that the complete opposite was occurring. He stated in *Discover* magazine, "Before the industry got started, the tropical burning was actually decreasing the amount of **carbon dioxide** in the atmosphere." The study of smoke in Brazil led Crutzen to further examine what effects larger amounts of different kinds of smoke might have on the environment, such as smoke from a nuclear war.

The journal *Ambio* commissioned Crutzen and John Birks, his colleague from the University of Colorado, to investigate what effects nuclear war might have on the planet. Crutzen and Birks studied a simulated worldwide nuclear war. They theorized that the black carbon soot from the raging fires would absorb as much as 99% of the sunlight. This lack of sunlight, coined "nuclear winter," would be devastating to all forms of life. For this theory Crutzen was named "Scientist of the Year" by *Discover* magazine in 1984, and awarded the prestigious Tyler Award four years later.

Because of the discoveries by Crutzen and other environmental scientists, a crucial international treaty was established in 1987. The Montreal Protocol was negotiated under the auspices of the United Nations and signed by 70 countries to slowly phase out the production of chlorofluorocarbons and other ozone-damaging chemicals by the year 2000. However, the United States had ended the production of CFCs five years earlier, in 1995. According to the *New York Times*, "the National Oceanic and Atmospheric Administration reported in 1994, while ozone over the South Pole is still decreasing, the depletion appears to be leveling off." Even though the ban has been established, existing CFCs will continue to reach the ozone, so the depletion will continue for some years. The full recovery of the ozone is not expected for at least 100 years.

From 1977 to 1980, Crutzen was director of the Air Quality Division, National Center for Atmospheric Research (NCAR), located in Boulder, Colorado. While at NCAR, he taught classes at Colorado State University in the department of Atmospheric Sciences. Since 1980, he has been a member of the Max Planck Society for the Advancement of Science, and he is the director of the Atmospheric Chemistry division at Max Planck Institute for Chemistry. In addition to Crutzen's position at the institute, he is a part-time professor at Scripps Institution of **Oceanography** at the University of California. In 1995, he was the recipient of the United Nations Environmental Ozone Award for outstanding contribution to the protection of the ozone layer. Crutzen has co-authored and edited several books, as well as having published several hundred articles in specialized publications.

See also Global warming; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ozone layer depletion



Microscopic view of granite porphyry crystals. © *Lester V. Bergman/Corbis. Reproduced by permission.*

CRYSTALS AND CRYSTALLOGRAPHY

A crystal is a patterned three-dimensional assembly of atoms that is a repetitive (periodic) array of atoms. Crystals contain repeating arrays or atoms arranged in unit cells. Crystallography is the study of the formation processes that produce crystals, and of the structural and identifying details of crystals.

In the ancient and medieval world, crystals were considered a strange union of the animal and mineral kingdoms, growing into predetermined shapes like living things but seemingly without life. Many mineralogists hypothesized that their growth was the result of astrological forces. It was not until Robert Boyle and Robert Hooke began experimenting with microscopes that the true nature of crystals began to be understood. During the course of the last three centuries an entire field of study, crystallography, developed to further the understanding of crystals.

All solid matter is either **amorphous** (without definite shape) or crystalline (from the Greek word for clear **ice**). Crystals are defined by a regular, well-ordered molecular structure called a lattice, consisting of stacked planes of molecules. Because the molecules of the crystal fit together and contain strong electrical attractions between the atoms, a crystal is typically very strong.

There are many shapes in which crystals may be found, depending upon the type of atomic bond that is most dominant within their molecules (e.g., ionic, covalent, or metallic). Crystals high in ionic bonds are often cubic; these include salt and sugar, as well as **iron** pyrite. Covalent bonds are very strong, producing an extremely durable crystal such as a **diamond**. Metallic bonds are typified by a cloud of free-roaming electrons, giving the compound's shape less definition but allowing for great electrical and thermal conductivity; most **metals** are technically crystals very high in metallic bonds.

All crystals are formed from tiny atomic building blocks called unit cells. By changing the way the unit cells are stacked together, seven different crystal structures can be formed: triclinic, monoclinic, orthorhombic, trigonal, tetragonal, hexagonal, and cubic. In addition to their structure, crystals are classified by their symmetry—that is, the ability of the crystal to look the same when rotated. Some crystals are symmetrical along two axes, some along three axes, and some along four axes; some display no symmetry at all.

Throughout history, many crystalline materials, including most **gemstones**, have been prized for their ability to be cut along flat planes called cleavage faces. This is accomplished by separating one lattice plane from the next, producing a surface that is almost perfectly flat. However, not all crystals allow such clean cuts. Many substances such as metal, stone, and brick behave like crystals but are very difficult to cut along a cleavage face.

Because of the many industrial and scientific applications of crystals, the demand for clear, perfectly formed samples is very high. Unfortunately, nature rarely produces such crystals; more often the crystal has faults or impurities; and it is for this reason that large, perfect gemstones are valued so highly. In order to meet the demand for pure crystals, scientists have developed methods for "growing" crystals. One common method is simply to melt a large supply of unrefined crystal and allow it to reform; while in a liquid state, the molten crystal is often sifted of impurities, in order to yield crystals of higher quality. Another method for growing crystals is called seeding. Here, a small sample of crystal is placed in a vapor or solution; material is allowed to accumulate on the seed until the system reaches equilibrium. Often in crystal seeding a seed of a different material than that of the crystal is used. This is the case in the natural crystal formation called **cloud seeding**, wherein seeds of silver iodide are dropped into **clouds**; the silver iodide accumulates ice crystals which eventually fall in the form of rain or snow.

Scientists began to investigate the nature of crystals as early as the seventeenth century, when the Danish geologist Nicolaus Steno (1638-1686) began his experiments with common crystals. He found that all crystals of a certain compound have characteristic angles at which the faces will meet. This means that every piece of salt will be cubic in shape, and that smashing a piece of salt will yield smaller and smaller cubes. Thus began the science of crystallography, and Steno's observation became its first law.

The next great crystallographer was the French mineralogist René-Just Haüy (1743–1822), who became involved in the science quite accidentally. While browsing through a friend's mineral collection, he dropped a large sample of calcite. He was surprised to note that the sample shattered along straight planes. Although Steno had pointed this out more than a century before, it was Haüy who hypothesized the existence of unit cells, showing how basic cells could be combined to create the different crystal shapes.

By the early 1800s many physicists were experimenting with crystals; in particular, they were fascinated by their ability to bend light and separate it into its component colors. Because of their varying molecular structures, different crystal types would affect light differently. Among the most influential member of the emerging field of optical **mineralogy** was the British scientist David Brewster; by 1819, Brewster had succeeded in classifying most known crystals according to their optical properties.

During the mid-l800s the preeminent French chemist Louis Pasteur examined tartrate crystals under a microscope; these crystals were known to twist the path of light sometimes one direction and sometimes the opposite. He found that the tartrate crystals were not all identical and that some were mirror images of the others. When combined, the two shapes within the whole tartrate would bend light in two possible directions. By using tweezers, Pasteur painstakingly separated the crystals into two piles, which were melted and then reformed into two distinct crystals. Once separated, each new crystal would twist light in only one direction, one clockwise, the other counterclockwise.

Pasteur's work became the foundation for crystal polarimetry, a method by which light is polarized, or aligned to a single plane. It was soon discovered that other crystals were also capable of polarizing light. Today, crystal polarimetry is used extensively in **physics** and optics.

Another phenomenon displayed by certain crystals is piezoelectricity. From a Greek work meaning "to press," piezoelectricity is the creation of an electrical potential by squeezing certain crystals. This strange effect was first discovered by **Pierre Curie** and his brother, Jacques, in 1880, who were surprised to detect a voltage across the face of compressed Rochelle salt.

The piezoelectric effect also works in reverse: when an electrical current is applied to a crystal such as **quartz**, it will contract; if the direction of the current is reversed, the crystal will expand. If an alternating current is used, the piezoelectric crystal will expand and contract rapidly, producing a vibration whose frequency can be regulated. Because of their precise vibrations, piezoelectric crystals are used in radio transmitters and quartz timepieces.

Perhaps the most important application of crystals is in the science of x-ray crystallography. Experiments in this field were first conducted by the German physicist Max von Laue. While an instructor at the University of Munich, Laue had done extensive work with diffraction gratings (metal meshes used to separate light into its component colors). His goal was to apply these gratings to the study of x-ray radiation because, at this time the true nature of x rays was yet to be fully understood. However, the wavelengths of x rays were far too short for diffraction gratings to be used, the x rays would pass through the holes unaffected. What was needed was a grating with microscopically tiny holes; unfortunately, the technology did not exist to construct such a grating.

In 1912, Laue perceived that the regular stacked-plane structure of a crystal would act like a very small diffraction grating; this hypothesis was successfully tested with a crystal of zinc sulfide, and x-ray crystallography was born. Using a crystal, scientists could now measure the wavelength of any x ray as long as they knew the internal structure of their crystal. Also, if an x ray of a known wavelength was used, the molecular structure of unknown crystals could be determined.

X-ray crystallography was perfected just a few years later by the father-son team of William Henry Bragg (1862–1942) and William Lawrence Bragg (1890–1971), who were awarded the 1915 Nobel Prize in physics for their work. Since that time, x-ray crystallography has been used to examine the molecular structure of thousands of crystalline substances and was instrumental in the analysis of DNA. Crystallography remains an important branch of **earth science** because the analysis and study of crystals often yields important information concerning the type and rate of geological processes.

See also Atomic theory; Cave minerals and speleothems; Chemical bonds and physical properties; Minerals; Mineralogy

CUMULIFORM CLOUD • *see* CLOUDS AND CLOUD TYPES

CUMULONIMBUS CLOUD • *see* CLOUDS AND CLOUD TYPES

CUMULUS CLOUD • *see* CLOUDS AND CLOUD TYPES

CURIE, MARIE (1867-1934)

Polish-born French physicist

Marie Curie was the first woman to win a Nobel Prize, and one of very few scientists ever to win that award twice. In collaboration with her physicist-husband **Pierre Curie**, Marie Curie developed and introduced the concept of **radioactivity** to the world. Working in primitive laboratory conditions, Curie investigated the nature of high-energy rays spontaneously produced by certain elements, and isolated two new radioactive elements, polonium and radium. Her scientific efforts also included the application of x rays and radioactivity to medical treatments.

Curie was born to her two-schoolteacher parents in Warsaw, Poland. Christened Maria Sklodowska, she was the fourth daughter and fifth child in the family. By the age of five, she had already begun to suffer deprivation. Her mother Bronislawa had contracted tuberculosis and assiduously avoided kissing or even touching her children. By the time Curie was 11, both her mother and her eldest sister Zosia died, leaving Marie an avowed atheist. Curie was also an avowed nationalist (like the other members in her family), and when she completed her elementary schooling, she entered Warsaw's "Floating University," an underground, revolutionary Polish school that prepared young Polish students to become teachers.

Curie left Warsaw at the age of 17, not for her own sake but for that of her older sister Bronya. Both sisters desired to acquire additional education abroad, but the family could not afford to send either of them, so Marie took a job as a governess to fund her sister's medical education in Paris. At first, she accepted a post near her home in Warsaw, then signed on with the Zorawskis, a family who lived some distance from Warsaw. Curie supplemented her formal teaching duties there with the organization of a free school for the local peasant children. Casimir Zorawski, the family's eldest son, eventually fell in love with Curie and she agreed to marry him, but his parents objected vehemently. Stunned by her employers' rejection, Curie finished her term with the Zorawskis and sought another position. She spent a year in a third governess job before her sister Bronya finished medical school and summoned her to Paris.

In 1891, at the age of 24, Curie enrolled at the Sorbonne and became one of the few women in attendance at the university. Although Bronya and her family back home were helping Curie pay for her studies, living in Paris was quite expensive. Too proud to ask for additional assistance, she subsisted on a diet of buttered bread and tea, which she augmented sometimes with fruit or an egg. Because she often went without heat, she would study at a nearby library until it closed. Not surprisingly, on this regimen she became anemic and on at least one occasion fainted during class.

Marie Curie. ***AP/Wide World. Reproduced by permission.***

In 1893, Curie received a degree in **physics**, finishing first in her class. The following year, she received a master's degree, this time graduating second in her class. Shortly thereafter, she discovered she had received the Alexandrovitch Scholarship, which enabled her to continue her education free of monetary worries. Many years later, Curie became the first recipient ever to pay back the prize. She reasoned that with that money, yet another student might be given the same opportunities she had.

Friends introduced Marie to Pierre Curie in 1894. The son and grandson of doctors, Pierre had studied physics at the Sorbonne; at the time he met Marie, he was the director of the École Municipale de Physique et Chimie Industrielles. The two became friends, and eventually she accepted Pierre's proposal of marriage. Their Paris home was scantily furnished, as neither had much interest in housekeeping. Rather, they concentrated on their work. Pierre Curie accepted a job at the School of Industrial Physics and Chemistry of the City of Paris, known as the EPCI. Given lab space there, Marie Curie spent eight hours a day on her investigations into the magnetic qualities of steel until she became pregnant with her first child, Irene, who was born in 1897.

Curie then began work in earnest on her doctorate. Like many scientists, she was fascinated by French physicist Antoine-Henri Becquerel's discovery that the element uranium emitted rays that contained vast amounts of energy. Unlike Wilhelm Röntgen's x rays, which resulted from the excitation of atoms from an outside energy source, the "Becquerel rays" seemed to be a naturally occurring part of the uranium ore. Using the piezoelectric **quartz** electrometer developed by Pierre and his brother Jacques, Marie tested all the elements then known to see if any of them, like uranium, caused the nearby air to conduct **electricity**. In the first year of her research, Curie coined the term "radioactivity" to describe this mysterious force. She later concluded that only thorium and uranium and their compounds were radioactive.

While other scientists had also investigated the radioactive properties of uranium and thorium, Curie noted that the **minerals** pitchblende and chalcolite emitted more rays than could be accounted for by either element. Curie concluded that some other radioactive element must be causing the greater radioactivity. To separate this element, however, would require a great deal of effort, progressively separating pitchblende by chemical analysis and then measuring the radioactivity of the separate components. In July, 1898, she and Pierre successfully extracted an element from this ore that was even more radioactive than uranium; they called it polonium in honor of Marie's homeland. Six months later, the pair discovered another radioactive substance—radium—embedded in the pitchblende.

Although the Curies had speculated that these elements existed, to prove their existence they still needed to describe them fully and calculate their atomic weight. In order to do so, Curie needed an abundant supply of pitchblende and a better laboratory. She arranged to get hundreds of kilograms of waste scraps from a pitchblende mining firm in her native Poland, and Pierre Curie's EPCI supervisor offered the couple the use of a laboratory space. The couple worked together, with Marie performing the physically arduous job of chemically separating the pitchblende and Pierre analyzing the physical properties of the substances that Marie's separations produced. In 1902, the Curies announced that they had succeeded in preparing a decigram of pure radium chloride and had made an initial determination of radium's atomic weight. They had proven the chemical individuality of radium.

Pierre Curie's father had moved in with the family and assumed the care of their daughter, Irene, so the couple could devote more than eight hours a day to their work. Pierre Curie's salary, however, was not enough to support the family, so Marie took a position as a lecturer in physics at the École Normal Supérieure; she was the first woman to teach there. In the years between 1900 and 1903, Curie published more than she had or would in any other three-year period, with much of this work being co-authored by Pierre Curie. In 1903, Curie became the first woman to complete her doctorate in France, summa cum laude.

The year Curie received her doctorate was also the year she and her husband began to achieve international recognition for their research. In November, the couple received England's prestigious Humphry Davy Medal, and the following month Marie and Pierre Curie—along with Becquerel—received the Nobel Prize in physics for their efforts in expanding scientific knowledge about radioactivity. Although Curie was the first woman ever to receive the prize, she and Pierre declined to attend the award ceremonies, pleading they were too tired to travel to Stockholm. The prize money from the Nobel, combined with that of the Daniel Osiris Prize—which she received soon after—allowed the couple to expand their research efforts. In addition, the Nobel bestowed upon the couple an international reputation that furthered their academic success. The year after he received the Nobel, Pierre Curie was named professor of physics of the Faculty of Sciences at the Sorbonne. Along with his post came funds for three paid workers, two laboratory assistants and a laboratory chief, stipulated to be Marie. This was Marie's first paid research position.

In 1904, Marie gave birth to another daughter. Despite the fact that both Pierre and Marie frequently suffered adverse effects from the radioactive materials with which they were in constant contact, their infant daughter was born healthy. The Curies continued their work regimen, taking sporadic vacations in the French countryside with their two children. They had just returned from one such vacation when in April 1906, tragedy struck; while walking in the congested street traffic of Paris, Pierre was run over by a heavy wagon and killed.

A month after the accident, the University of Paris invited Curie to take over her husband's teaching position. Upon acceptance she became the first woman to ever receive a post in higher education in France, although she was not named to a full professorship for two more years. During this time, Curie came to accept the theory of English physicists Ernest Rutherford and Frederick Soddy that radioactivity was caused by atomic nuclei losing particles, and that these disintegrations caused the transmutation of an atomic nucleus into a different element. It was Curie, in fact, who coined the terms disintegration and transmutation.

In 1909, Curie received an academic reward that she had greatly desired: the University of Paris drew up plans for an Institut du Radium that would consist of two branches, a laboratory to study radioactivity—which Curie would run—and a laboratory for biological research on radium therapy, to be overseen by a physician. It took five years for the plans to come to fruition. In 1910, however, with her assistant André Debierne, Curie finally achieved the isolation of pure radium metal, and later prepared the first international standard of that element.

Curie was awarded the Nobel Prize again in 1911, this time "for her services to the advancement of chemistry by the discovery of the elements radium and polonium," according to the award committee. The first scientist to win the Nobel twice, Curie devoted most of the money to her scientific studies. During World War I, Curie volunteered at the National Aid Society, then brought her technology to the war front and instructed army medical personnel in the practical applications of radiology. With the installation of radiological equipment in ambulances, for instance, wounded soldiers would not have to be transported far to be x-rayed. When the war ended, Curie returned to research and devoted much of her time to her work.

By the 1920s, Curie was an international figure; the Curie Foundation had been established in 1920 to accept private donations for research, and two years later the scientist was invited to participate on the League of Nations International Commission for Intellectual Cooperation. Her health was failing, however, and she was troubled by fatigue and cataracts. Despite her discomfort, Curie made a highly publicized tour of the United States in 1921. The previous year, she had met Missy Meloney, editor of the *Delineator*, a woman's magazine. Horrified at the conditions in which Curie lived and worked (the Curies had made no money from their process for producing radium, having refused to patent it), Meloney proposed that a national subscription be held to finance a gram of radium for the institute to use in research. The tour proved grueling for Curie; by the end of her stay in New York, she had her right arm in a sling, the result of too many too strong handshakes. However, with Meloney's assistance, Curie left America with a valuable gram of radium.

Curie continued her work in the laboratory throughout the decade, joined by her daughter, Irene Joliot-Curie, who was pursuing a doctoral degree just as her mother had done. In 1925, Irene successfully defended her doctoral thesis on alpha rays of polonium, although Curie did not attend the defense lest her presence detract from her daughter's performance. Meanwhile, Curie's health still continued to fail and she was forced to spend more time away from her work in the laboratory. The result of prolonged exposure to radium, Curie contracted leukemia and died in 1934, in a nursing home in the French Alps. She was buried next to Pierre Curie in Sceaux, France.

See also History of exploration III (Modern era)

CURIE, PIERRE (1859-1906)

French physicist

Pierre Curie was a physicist who became famous for his collaboration with his wife **Marie Curie** in the study of **radioactivity**. Before joining his wife in her research, Pierre Curie was already widely known and respected in the world of **physics**. He discovered (with his brother Jacques) the phenomenon of piezoelectricity—in which a crystal can become electrically polarized—and invented the **quartz** balance. His papers on crystal symmetry and his findings on the relation between **magnetism** and **temperature** also earned praise in the scientific community.

Pierre Curie was born in Paris, the son of Sophie-Claire Depouilly, daughter of a formerly prominent manufacturer, and Eugène Curie, a free-thinking physician who was also a physician's son. Dr. Curie supported the family with his modest medical practice while pursuing his love for the natural sciences on the side. He was also an idealist and an ardent republican who set up a hospital for the wounded during the Commune of 1871. Pierre was a dreamer whose style of learning was not well adapted to formal schooling. He received his pre-university education entirely at home, taught first by his mother and then by his father as well as his older brother, Jacques. He especially enjoyed excursions into the countryside to observe and study plants and animals, developing a love of nature that endured throughout his life and that provided his only recreation and relief from work during his later scientific career. At the age of 14, Curie studied with a mathematics professor who helped him develop his gift in the subject, especially spatial concepts. Curie's knowledge of physics and mathematics earned him his Bachelor of Science degree in 1875 at the age of 16. He then enrolled in the Faculty of Sciences at the Sorbonne in Paris and earned his *licence* (the equivalent of a master's degree) in physical sciences in 1877.


Pierre Curie. ***Library of Congress.***

Curie became a laboratory assistant to Paul Desains at the Sorbonne in 1878, in charge of the physics students' lab work. His brother Jacques was working in the **mineralogy** laboratory at the Sorbonne at that time, and the two began a productive five-year scientific collaboration. They investigated pyroelectricity, the acquisition of electric charges by different faces of certain types of **crystals** when heated. Led by their knowledge of symmetry in crystals, the brothers experimentally discovered the previously unknown phenomenon of piezoelectricity, an electric polarization caused by force applied to the crystal. In 1880, the Curies published the first in a series of papers about their discovery. They then studied the opposite effect—the compression of a piezoelectric crystal by an electric field. In order to measure the very small amounts of **electricity** involved, the brothers invented a new laboratory instrument: a piezoelectric quartz electrometer, or balance. This device became very useful for electrical researchers and would prove highly valuable to Marie Curie in her studies of radioactivity. Much later, piezoelectricity had important practical applications. Paul Langevin, a student of Pierre Curie's, found that inverse piezoelectricity causes piezoelectric quartz in alternating fields to emit high-frequency sound waves, which were used to detect submarines and explore the ocean's floor. Piezoelectric crystals were also used in radio broadcasting and stereo equipment.

In 1882, Pierre Curie was appointed head of the laboratory at Paris' new Municipal School of Industrial Physics and Chemistry, a poorly paid position; he remained at the school for 22 years, until 1904. In 1883, Jacques Curie left Paris to become a lecturer in mineralogy at the University of Montpelier, and the brothers' collaboration ended. After Jacques's departure, Pierre delved into theoretical and experimental research on crystal symmetry, although the time available to him for such work was limited by the demands of organizing the school's laboratory from scratch and directing the laboratory work of up to 30 students, with only one assistant. He began publishing works on crystal symmetry in 1884, including in 1885, a theory on the formation of crystals and in 1894, an enunciation of the general principle of symmetry. Curie's writings on symmetry were of fundamental importance to later crystallographers, and, as Marie Curie later wrote in *Pierre Curie*, "he always retained a passionate interest in the physics of crystals" even though he turned his attention to other areas.

From 1890 to 1895, Pierre Curie performed a series of investigations that formed the basis of his doctoral thesis: a study of the magnetic properties of substances at different temperatures. He was, as always, hampered in his work by his obligations to his students, by the lack of funds to support his experiments, and by the lack of a laboratory or even a room for his own personal use. His **magnetism** research was conducted mostly in a corridor. In spite of these limitations, Curie's work on magnetism, like his papers on symmetry, was of fundamental importance. His expression of the results of his findings about the relation between temperature and magnetization became known as Curie's Law, and the temperature above which magnetic properties disappear is called the Curie point. Curie successfully defended his thesis before the Faculty of Sciences at the University of Paris (the Sorbonne) in March 1895, thus earning his doctorate. Also during this period, he constructed a periodic precision balance, with direct reading, that was a great advance over older balance systems and was especially valuable for chemical analysis. Curie was now becoming well known among physicists; he attracted the attention and esteem of, among others, the noted Scottish mathematician and physicist William Thomson (Lord Kelvin). It was partly due to Kelvin's influence that Curie was named to a newly created chair of physics at the School of Physics and Chemistry, which improved his status somewhat but still did not bring him a laboratory.

In the spring of 1894, at the age of 35, Curie met Maria (later Marie) Sklodowska, a poor young Polish student who had received her *licence* in physics from the Sorbonne and was then studying for her *licence* in mathematics. They immediately formed a rapport, and Curie soon proposed marriage. Sklodowska returned to Poland that summer, not certain that she would be willing to separate herself permanently from her family and her country. Curie's persuasive correspondence convinced her to return to Paris that autumn, and the couple married in July 1895, in a simple civil ceremony. Marie used a wedding gift of cash to purchase two bicycles, which took the newlyweds on their honeymoon in the French countryside and provided their main source of recreation for years to come. Their daughter Irene was born in 1897, and a few days later Pierre's mother died; Dr. Curie then came to live with the young couple and helped care for his granddaughter.

The Curies' attention was caught by Henri Becquerel's discovery in 1896 that uranium compounds emit rays. Marie decided to make a study of this phenomenon the subject of her doctor's thesis, and Pierre secured the use of a ground-floor storeroom/machine shop at the School for her laboratory work. Using the Curie brothers' piezoelectric quartz electrometer, Marie tested all the elements then known to see if any of them, like uranium, emitted "Becquerel rays," which she christened "radioactivity." Only thorium and uranium and their compounds, she found, were radioactive. She was startled to discover that the ores pitchblende and chalcolite had much greater levels of radioactivity than the amounts of uranium and thorium they contained could account for. She guessed that a new, highly radioactive element must be responsible and, as she wrote in *Pierre Curie*, was seized with "a passionate desire to verify this hypothesis as rapidly as possible."

Pierre Curie too saw the significance of his wife's findings and set aside his much-loved work on crystals (only for the time being, he thought) to join Marie in the search for the new element. They devised a new method of chemical research, progressively separating pitchblende by chemical analysis and then measuring the radioactivity of the separate constituents. In July 1898, in a joint paper, they announced their discovery of a new element they named polonium, in honor of Marie Curie's native country. In December 1898, they announced, in a paper issued with their collaborator G. Bémont, the discovery of another new element, radium. Both elements were more radioactive than uranium or thorium.

The Curies had discovered radium and polonium, but in order to prove the existence of these new substances chemically, they had to isolate the elements so the atomic weight of each could be determined. This was a daunting task, as they would have to process two tons of pitchblende ore to obtain a few centigrams of pure radium. Their laboratory facilities were woefully inadequate: an abandoned wooden shed in the School's yard, with no hoods to carry off the poisonous gases their work produced. They found the pitchblende at a reasonable price in the form of waste from a uranium mine run by the Austrian government. The Curies now divided their labor. Marie acted as the chemist, performing the physically arduous job of chemically separating the pitchblende; the bulkiest part of this work she did in the yard adjoining the shed/laboratory. Pierre was the physicist, analyzing the physical properties of the substances that Marie's separations produced. In 1902, the Curies announced that they had succeeded in preparing a decigram of pure radium chloride and had made an initial determination of radium's atomic weight. They had proven the chemical individuality of radium.

The Curies' research also yielded a wealth of information about radioactivity, which they shared with the world in a series of papers published between 1898 and 1904. They announced their discovery of induced radioactivity in 1899. They wrote about the luminous and chemical effects of radioactive rays and their electric charge. Pierre studied the action of a **magnetic field** on radium rays, he investigated the persistence of induced radioactivity, and he developed a standard for measuring time on the basis of radioactivity, an important basis for geologic and archaeological dating techniques. Pierre Curie also used himself as a human guinea pig, deliberately exposing his arm to radium for several hours and recording the progressive, slowly healing burn that resulted. He collaborated with physicians in animal experiments that led to the use of radium therapy—often called "Curie-therapie" then—to treat cancer and lupus. In 1904, he published a paper on the liberation of heat by radium salts.

Through all this intensive research, the Curies struggled to keep up with their teaching, household, and financial obligations. Pierre Curie was a kind, gentle, and reserved man, entirely devoted to his work—science conducted purely for the sake of science. He rejected honorary distinctions; in 1903, he declined the prestigious decoration of the Legion of Honor. He also, with his wife's agreement, refused to patent their radium-preparation process, which formed the basis of the lucrative radium industry; instead, they shared all their information about the process with whoever asked for it. Curie found it almost impossible to advance professionally within the French university system; seeking a position was an "ugly necessity" and "demoralizing" for him (*Pierre Curie*), so posts he might have been considered for went instead to others. He was turned down for the Chair of Physical Chemistry at the Sorbonne in 1898; instead, he was appointed assistant professor at the Polytechnic School in March 1900, an inferior position.

Appreciated outside France, Curie received an excellent offer of a professorship at the University of Geneva in the spring of 1900, but he turned it down so as not to interrupt his research on radium. Shortly afterward, Curie was appointed to a physics chair at the Sorbonne, thanks to the efforts of Jules Henri Poincaré. Still, he did not have a laboratory, and his teaching load was now doubled, as he still held his post at the School of Physics and Chemistry. He began to suffer from extreme fatigue and sharp pains through his body, which he and his wife attributed to overwork, although the symptoms were almost certainly a sign of radiation poisoning, an unrecognized illness at that time. In 1902, Curie's candidacy for election to the French Academy of Sciences failed, and in 1903, his application for the chair of mineralogy at the Sorbonne was rejected, both of which added to his bitterness toward the French academic establishment.

Recognition at home finally came for Curie because of international awards. In 1903, London's Royal Society conferred the Davy medal on the Curies, and shortly thereafter they were awarded the 1903 Nobel Prize in physics—along with Becquerel—for their work on radioactivity. Curie presciently concluded his Nobel lecture (delivered in 1905 because the Curies were unable to attend the 1903 award ceremony) by wondering whether the knowledge of radium and radioactivity would be harmful for humanity. He added that he himself felt that more good than harm would result from the new discoveries. The Nobel award changed the Curies' reclusive work-absorbed life. They were inundated by journalists, photographers, curiosity-seekers, eminent and little known visitors, correspondence, and requests for articles and lectures. Still, the cash from the award was a relief, and the award's prestige finally prompted the French parliament to create a new professorship for Curie at the Sorbonne in 1904. Curie declared he would remain at the School of Physics unless the new chair included a fully funded laboratory, complete with assistants. His demand was met, and Marie was named his laboratory chief. Late in 1904, the Curies' second daughter was born. By early 1906, Pierre Curie was poised to begin work—at last and for the first time—in an adequate laboratory, although he was increasingly ill and tired. On April 19, 1906, leaving a lunchtime meeting in Paris with colleagues from the Sorbonne, Curie slipped in front of a horse-drawn cart while crossing a rain-slicked rue Dauphine. He was killed instantly when the rear wheel of the cart crushed his skull. True to the way he had conducted his life, he was interred in a small suburban cemetery in a simple, private ceremony attended only by his family and a few close friends. In his memory, the Faculty of Sciences at the Sorbonne appointed Curie's widow Marie to his chair.

CUTBANKS • *see* CHANNEL PATTERNS

CUVIER, GEORGES (1769-1832)

French naturalist

Georges Léopold Chrétien Frédéric Dagobert, Baron Cuvier was a French naturalist who is known as the founder of the field of paleontology, as well as the founder of comparative anatomy.

Cuvier was born in Montbeliard, near Basel. Although a French town, Cuvier's birthplace at that time belonged to the Duchy of Wërttemberg. Cuvier was an academically inclined young man and, because his family lived in near-poverty, he accepted the offer to study for free at the Karlsschule in Stuttgart, Germany. He graduated at eighteen, returned home, and then found employment as a tutor in Normandy. While working in Normandy, he familiarized himself with the marine creatures he found on the beach, which he dissected and drew in detail. While doing so, he referred to Aristotle's ideas of comparing different animal structures, Carl Linnaeus's *System of Nature* and Buffon's *Natural History of Animals*. His impressive marine animal drawings came to the attention of Geoffroy Saint-Hilaire, and eventually led to Cuvier's appointment as assistant professor of comparative anatomy at the Museum of Natural History in Paris. Under Napoleon's regime, Cuvier became inspector General in the Department of Education and contributed to significant education reform in France. After Napoleon's fall, Cuvier retained his position and became an accepted authority in science and education, and earned several promotions which include a professorship at the Collège de France and permanent secretary for the

Academy of Sciences. Cuvier died in 1832 of cholera, during the first major epidemic of that disease in **Europe**.

Prior to Cuvier, anatomists such as Louis Daubenton, Johann Friedrich Blumenbach, and Petrus Camper posited the human being as the fundamental form to which all other living creatures were compared. Cuvier, however, decided to create an objective system of comparative anatomy based on observation. His initial field of research was marine animals, particularly mollusks, worms, and various fishes. Later, he extended his investigations to vertebrates in general. The conceptual framework of Cuvier's research was a systematic method of comparative anatomy. According to Cuvier, living beings exhibit certain distinctive anatomic features that enable the scientist to place an individual specimen in the larger context of a general anatomic system. For example, one can make significant generalizations by observing individual features such as dental structure, foot structure, skull shape, etc. Cuvier's comparative research, which expanded from the study of vertebrates to include the entire animal kingdom, was presented in his work *The Animal Kingdom, Distributed According to Its Organization* (1817). While Cuvier's work did not contribute any new facts to the science of anatomy, his method earned him high praise and esteem in the scientific community.

An important element of Cuvier's methodology is his **correlation** theory, which posits the functional interdependence of particular organs within an in individual organism. For example, as Cuvier observed, carnivorous animals possess certain distinctive features that clearly separate them from, say, herbivores. These features include sharp teeth, a certain jaw structure, a digestive system adapted to meat, acute eyesight, sharp claws, powerful and swift locomotion, etc.

In Paris, which is in a calcareous **area**, Cuvier applied his comparative method to study **fossils**. In his carefully organized excavations, particular attention was paid to the specific location, position, and placement of the discovered fossils. In addition, using his correlation theory, he developed a reconstruction method that enabled researchers to identify incomplete skeletons. Furthermore, in order to validate a particular hypothesis concerning the identity of an incomplete skeleton, Cuvier would compare the extinct animal to its closest living relative, in an effort to complete the puzzle. These investigations were described in his seminal *Investigations on Fossil Bones* (1812), establishing Cuvier as the founder of modern paleontology. Using his comparative method, with particular emphasis on dentition and bone structure Cuvier was able to demonstrate that the two types of elephant, Indian and African, classified as examples of one species, in reality constituted two distinct species. In fact, Cuvier found that the extinct mammoth is closer to the Indian elephant than the two existing elephant species are to each other. Extending his research on elephants to Pachydermata in general, Cuvier studied both existing and extinct forms, identifying several new genera, including Palaeotherium and Dinotherium. In addition, he provided the first scientific description of the American giant sloth and named the pterodactyl.

Cuvier, like many of his colleagues, puzzled over the seemingly mysterious fact that animal forms changed through history. However, unlike some his colleagues, who approached the issue with extreme circumspection, Cuvier decided that species do not change. "The immutability of species," wrote Nordenskiöld, "is to Cuvier's mind an absolute fact." In order to explain why certain species were extinct and why fossils of some extinct creatures were unrecognizable from modern creatures, Cuvier invoked the **catastrophism** theory, which posits that a "new" species appear after the extinction, due to a violent upheaval (such as an **earthquake**) of its "old" counterpart. Thus, for example, Cuvier denied the existence of human fossils, asserting that, for example, lion fossils and lions in their present form represent two distinct species. Realizing the absurdity of the idea that species emerged out of nothing following a catastrophe, Cuvier attempted the explain the continuity of life by positing a type of near-extinction, which would allow the survival of small populations of a particular species, positing, as Cassirer has remarked, an **evolution** by analogy, whereby a particular species would be replaced by its new analogue, which to his mind seemed more reasonable than the notion of gradual evolution.

Cuvier's views of classification and evolution were vigorously opposed by several of his prominent contemporaries, who found his systematic philosophy, particularly his adamant insistence of four ground-plans, dogmatic. For example, Geoffroy Saint-Hilaire, who engaged Cuvier in a lengthy polemic, maintained that, because life manifests itself on the basis of a fundamental, indivisible impulse, Cuvier's claim that creatures emerging from different ground plans that cannot be compared does not reflect the true nature of the animal world. Accused by his critics for speculative dogmatism, Cuvier nevertheless, as Cassirer has written, defended his views on the basis of empirical research. As scholars have observed, the polemic between Cuvier and Saint-Hilaire was never resolved owing to the both antagonist defended points of view, which, while seemingly opposed, contributed, as complementary views, to the progress of life sciences and Earth sciences.

See also Evolution, evidence of; Evolutionary mechanisms; Fossil record; Fossils and fossilization

CYCLOSILICATES

The most abundant rock-forming **minerals** in the **crust** of the Earth are the silicates. They are formed primarily of **silicon** and **oxygen**, together with various **metals**. The fundamental unit of these minerals is the silicon-oxygen tetrahedron. These tetrahedra have a pyramidal shape, with a relatively small, positively charged silicon cation (Si^{+4}) in the center and four larger, negatively charged oxygen anions (O^{-2}) at the corners, producing a net charge of –4. **Aluminum** cations (Al^{+3}) may substitute for silicon, and various anions such as hydroxyl (OH^{-}) or fluorine (F^{-}) may substitute for oxygen. In order to form stable minerals, the charges that exist between tetrahedra must be neutralized. This can be accomplished by the sharing of oxygen cations between tetrahedra, or by the binding together adjacent tetrahedra with various metal cations. This in turn creates characteristic silicate structures that can be used to classify silicate minerals into cyclosilicates, **inosilicates**, **nesosilicates**, **phyllosilicates**, **sorosilicates**, and **tectosilicates**.

In cyclosilicates, the tetrahedra form rings of 3, 4, or 6 tetrahedra. However, most cyclosilicates are formed from a framework of six tetrahedra, giving them the formula $(Si_6O_{18})^{-12}$, and examples of this type of mineral includes the **gemstones** beryl (including the varieties emerald and aquamarine, and tourmaline. Beryl, found in **granite**, pegmatites, and mica **schist**, has the chemical formula $Be_3Al_2(Si_6O_{18}$. Deposits of beryl that are not of gem quality are an important ore of the metal beryllium. Minerals in the tourmaline group, found in granite pegmatites and as accessory minerals in igneous and metamorphic rocks, can also be present in veins and as a detrital mineral in sediments and sedimentary **rock**. Varieties of tourmaline include schorlite, also called black tourmaline or **iron** tourmaline, $NaFe_3B_3Al_3(OH)\ _4(Al_3Si_6O_{27})$; dravite, also called brown tourmaline or magnesium tourmaline, $NaMg_3B_3Al_3(OH)_4(Al_3Si_6O_{27})$, and elbaite, a lighter-colored, lithium-bearing variety also called alkali tourmaline, $Na_2Li_3B_6Al_9(OH)_8(Al_3Si_6O_{27})_2$.

D

DARCEY, HENRY PHILIBERT GASPARD

(1803-1858)

French engineer

Henry Philibert Gaspard Darcy (1803–1858) was an accomplished French engineer, researcher, and civil servant, who is credited with building roads, **water** systems, and railroads. He is best known for a number of major contributions and advances in the understanding of fluid flow in pipes, open channels, and porous media. Darcy was the first researcher to suspect the existence of the boundary layer in fluid flow. His work contributed in the development of the Darcy-Weisbach equation, recognized as the best empirical relation for pipe flow resistance. Darcy also made major contributions to open channel flow research and provided the first quantitative measurements of **artesian** well flow. An enduring legacy of his work, Darcy's Law for flow in porous media, a cornerstone for several fields of study including ground-water hydrology, **soil physics**, and **petroleum** engineering remains widely used.

Darcy was born on June 10, 1803 in Dijon, France, the son of a civil servant. In 1821, he entered L'Ecole Polytechnique in Paris. In 1823 he was admitted to the prestigious L'Ecole des Ponts et Chaussee's (School of Bridges and Roads) in Paris, where he graduated with a degree in Civil Engineering in 1826. After graduation, he took a position with the Corps of Bridges and Roads in Dijon. There, Darcy began work on a project to develop a system for a safe and adequate water supply for the city. That effort eventually resulted in completion in 1844 of a model, completely enclosed, **gravity** driven system that provided water to major buildings and street hydrants throughout the city. Darcy's work was so advanced that it was 20 years before Paris had similar service. Despite his impressive achievements, Darcy refused to accept payment for his work as designer and manager of the water system project. The amount of money Darcy refused would translate to over a million dollars at modern exchange rates.

Darcy completed numerous other civil works in and near Dijon including roadways, bridges, sewers, and a railroad, passing through Dijon, linking Paris with Lyon, the largest industrial city to the south. His design for the railroad included a 2.5-mile-long (4 km) tunnel through the mountains at a time when tunnels of any significant length were considered unacceptable. However, Darcy had enlisted the aid of a geologist and mining engineer for a detailed survey of the site that indicated ideal conditions for constructing a tunnel. He had conceived the best engineering solution by rejecting an old generalization (tunnel length) and analyzed the problem on a site-specific basis. Because of Darcy's plan, the railroad passed through Dijon, ensuring the city's economic future. In 1844, he was awarded the Legion of Honor.

The St. Pierre Basin Fountain was considered a technological marvel for the time. Darcy designed separate valves for controlling an inner and outer ring of jets that allowed variations in the height of the fountain display. In an 1856 report, Darcy provided a theoretical analysis and experimental verification of the jet flow in this artesian system as a function of the height of the water system's two source reservoirs.

In 1848, Darcy was appointed Chief Director for Water and Pavements in Paris. There he began his systematic study of turbulent flow in pipes. He made significant advances in the design of the Pitot tube, used to measure the flow velocity in pipes. Those improvements made possible accurate, detailed measurements of point velocity distributions in pipes, leading to advances in pipe hydraulics and to his recognition of the existence of the boundary layer.

In 1855, Darcy returned to Dijon to carry out his famous **sand** column experiments that ultimately resulted in Darcy's law for flow in porous media. For one-dimensional flow, the law relates the volumetric flow rate to the cross-sectional **area** of a tube or column to the drop in hydraulic head over the length of the flow path, and introduces a proportionality constant for hydraulic conductivity. Subsequent to his work, engineers and scientists have demonstrated the theoretical basis and applicability of Darcy's law in several fields. The law has since been generalized to allow for differential solutions, vector analysis, and unsaturated and multiphase flow.

Darcy died unexpectedly of pneumonia, on January 3, 1858. He is buried in Dijon.

See also Hydrogeology; Hydrostatic pressure

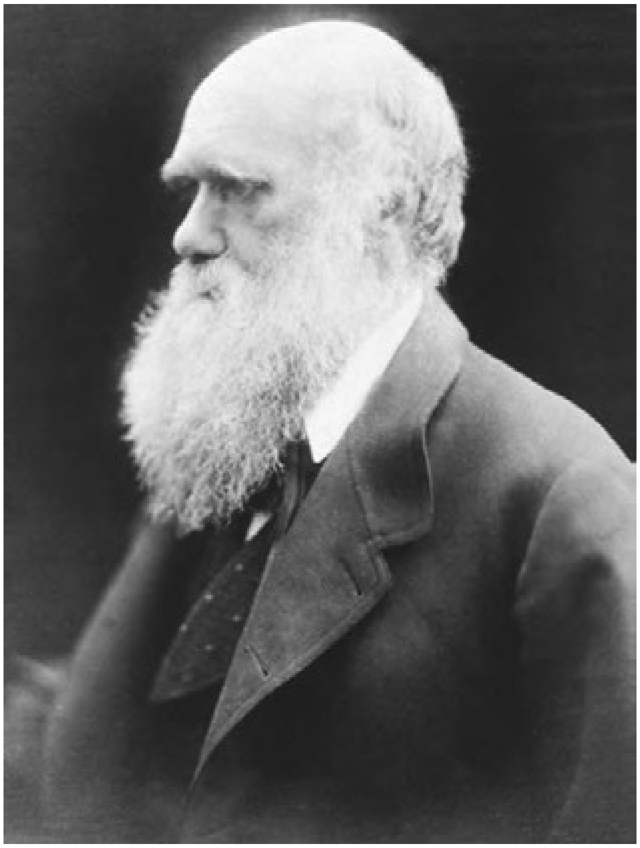
DARWIN, CHARLES ROBERT (1809-1882)

English naturalist

Charles Robert Darwin is credited with popularizing the concept of organic **evolution** by means of natural selection. Though Darwin was not the first naturalist to propose a model of biological evolution, his introduction of the mechanism of the "survival of the fittest" and discussion of the evolution of humans, marked a revolution in both science and natural philosophy.

Darwin was born in Shrewsbury, England and showed an early interest in the natural sciences, especially **geology**. His father, Robert Darwin, a wealthy physician, encouraged Charles to pursue studies in medicine at the University of Edinburg. Darwin soon tired of the subject, and his father sent him to Cambridge to prepare for a career in the clergy. At Cambridge, Darwin rekindled his passion for the natural sciences, often devoting more time to socializing with Cambridge scientists than to his clerical studies. With guidance from his cousin, entomologist William Darwin Fox (1805–1880), Darwin became increasingly involved in the growing circle of natural scientists at Cambridge. Fox introduced Darwin to clergyman and biologist John Stevens Henslow (1796–1861). Henslow became Darwin's tutor in mathematics and theology, as well as his mentor in his personal studies of botany, geology, and zoology. Henslow profoundly influenced Darwin, and it was he who encouraged Darwin to delay seeking an appointment in the Church of England in favor of joining an expedition team and venturing overseas. After graduation, Darwin agreed to an unpaid position as naturalist aboard the H.M.S. *Beagle*. The expedition team was initially chartered for a three year voyage and survey of South America's Pacific coastline, but the ship pursued other ventures after their work was complete and Darwin remained part of H.M.S. *Beagle's* crew for five years.

Darwin used his years aboard *The Beagle* to further his study of the natural sciences. In **South America**, Darwin became fascinated with geology. He paid close attention to changes in the land brought about by earthquakes and volcanoes. His observations led him to reject **catastrophism** (a theory that land forms are the result of single, catastrophic events), and instead espoused the geological theories of gradual development proposed by English geologist **Charles Lyell** (1797–1875) in his 1830 work, *Principles of Geology*. Yet, some of his observations in South America did not fit with Lyell's theories. Darwin disagreed with Lyell's assertion that **coral reefs** grew atop oceanic volcanoes and rises, and concluded that coral reefs built upon themselves. When Darwin returned to England in 1836, he and Lyell became good friends. Lyell welcomed Darwin's new research on coral reefs, and encouraged him to publish other studies from his voyages.



Charles Darwin. *Library of Congress.*

Darwin was elected a fellow of the Geological Society in 1836, and became a member of the Royal Society in 1839. That same year, he published his *Journal of Researches into the Geology and Natural History of the Various Countries Visited by H.M.S. Beagle*. Though his achievements in geology largely prompted his welcoming into Britain's scientific community, his research interests began to diverge from the discipline in the early 1840s. Discussions with other naturalists prompted Darwin's increasing interest in population diversity of fauna, extinct animals, and the presumed static nature of species. Again, he turned to notes of his observations and various specimens he gathered while on his prior expedition. The focus of his new studies was the Galápagos Islands off the Pacific coast of Ecuador. While there, Darwin was struck by the uniqueness of the island's tortoises and birds. Some neighboring islands had animal populations that were largely similar to that of the continent, while others had seemingly different variety of species. After analyzing finch specimens from the Galapagos, Darwin concluded that species must have some means of transmutation, or ability of a species to alter over time. Darwin thus proposed that as species modified, and as old species disappeared, new varieties could be introduced. Thus, Darwin proposed an evolutionary model of animal populations.

The idea of organic evolution was not novel. French naturalist, Georges Buffon (1707–1788) had theorized that species were prone to development and change. Darwin's own grandfather, Erasmus Darwin, also published research regarding the evolution of species. Although the theoretical concept of evolution was not new, it remained undeveloped prior to Charles Darwin. Just as he had done with Lyell's geological theory, Darwin set about to further the understanding of evolution not merely as a philosophical concept, but as a practical scientific model for explaining the diversity of species and populations. His major contribution to the field was the introduction of a mechanism by which evolution was accomplished. Darwin believed that evolution was the product of an ongoing struggle of species to better adapt to their environment, with those that were best adapted surviving to reproduce and replace less-suited individuals. He called this phenomenon "survival of the fittest," or natural selection. In this way, Darwin believed that traits of maximum adaptability were transferred to future generations of the animal population, eventually resulting in new species.

Darwin finished an extensive draft of his theories in 1844, but lacked confidence in his abilities to convince others of the merits of his discoveries. Years later, prompted by rumors that a colleague was about to publish a theory similar to his own, Darwin decided to release his research. *On the Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races in the Struggle for Life* was published November 1859, and became an instant bestseller.

A common misconception is that *On the Origin of Species* was the introduction of the concept of human evolution. In fact, a discussion of human antiquity is relatively absent from the book. Darwin did not directly address the relationship between animal and human evolution until he published *The Descent of Man, and Selection in Relation to Sex* in 1871. Darwin introduced not only a model for the biological evolution of man, but also attempted to chart the process of man's psychological evolution. He further tried to break down the barriers between man and animals in 1872, with his work *The Expression of the Emotions in Man and Animals.* By observing facial features and voice sounds, Darwin asserted that man and non-human animals exhibited signs of emotion in similar ways. In the last years of his career, Darwin took the concept of organic evolution to its logical end by applying natural selection and specialization to the plant kingdom.

Darwin's works on evolution met with both debate from the scientific societies, and criticism from some members of the clergy. *On the Origin of Species* and *The Descent of Man* were both published at a time of heightened religious evangelicalism in England. Though willing to discuss his theories with colleagues in the sciences, Darwin refrained from participating in public debates concerning his research. In the last decade of his life, Darwin was disturbed about the application of his evolutionary models to social theory. By most accounts, he considered the emerging concept of the social and cultural evolution of men and civilizations, which later became known as Social Darwinism, to be a grievous misinterpretation of his works. Regardless of his opposition, he remained publicly taciturn about the impact his scientific theories on theology, scientific methodology, and social theory. Closely guarding his privacy, Darwin retired to his estate in Down. He died at Down House in 1882. Though his wishes were to receive an informal burial, Parliament immediately ordered a state burial for the famous naturalist at Westminster Abby. By the time of his death, the scientific community had largely accepted the arguments favoring his theories of evolution. Although the later discoveries in genetics and molecular biology radically refined and reinterpreted Darwin's evolutionary mechanisms, evolutionary theory is the key and unifying theory in all biological science.

See also Evolution, evidence of; Evolutionary mechanisms

DATING METHODS

Dating techniques are procedures used by scientists to determine the age of a specimen. Relative dating methods tell only if one sample is older or younger than another sample; absolute dating methods provide a date in years. The latter have generally been available only since 1947. Many absolute dating techniques take advantage of radioactive decay, whereby a radioactive form of an element is converted into another radioactive isotope or non-radioactive product at a regular rate. Others, such as amino acid racimization and cation-ratio dating, are based on chemical changes in the organic or inorganic composition of a sample. In recent years, a few of these methods have undergone continual refinement as scientists strive to develop the most accurate dating techniques possible.

Relative dating methods determine whether one sample is older or younger than another. They do not provide an age in years. Before the advent of absolute dating methods, nearly all dating was relative. The main relative dating method is **stratigraphy**.

Stratigraphy is the study of layers of rocks or the objects embedded within those layers. It is based on the assumption (which, except at **unconformities**, nearly always holds true) that deeper layers were deposited earlier, and thus are older than more shallow layers. The sequential layers of **rock** represent sequential intervals of time. Although these units may be sequential, they are not necessarily continuous due to erosional removal of some intervening units. The smallest of these rock units that can be matched to a specific time interval is called a bed. Beds that are related are grouped together into members, and members are grouped into formations.

Seriation is the ordering of objects according to their age. It is a relative dating method. In a landmark study, archaeologist James Ford used seriation to determine the chronological order of American Indian pottery styles in the Mississippi Valley. Artifact styles such as pottery types are seriated by analyzing their abundances through time. This is done by counting the number of pieces of each style of the artifact in each stratigraphic layer and then graphing the data. A layer with many pieces of a particular style will be represented by a wide band on the graph, and a layer with only a few pieces will be represented by a narrow band. The bands are arranged into battleship-shaped curves, with each style getting its own curve.

The curves are then compared with one another, and from this the relative ages of the styles are determined. A limitation to this method is that it assumes all differences in artifact styles are the result of different periods of time, and are not due to the immigration of new cultures into the **area** of study.

The term faunal dating refers to the use of animal bones to determine the age of sedimentary layers or objects such as cultural artifacts embedded within those layers. Scientists can determine an approximate age for a layer by examining which species or genera of animals are buried in it. The technique works best if the animals belonged to species that evolved quickly, expanded rapidly over a large area, or suffered a mass extinction. In addition to providing rough absolute dates for specimens buried in the same stratigraphic unit as the bones, faunal analysis can also provide relative ages for objects buried above or below the fauna-encasing layers.

Each year seed-bearing plants release large numbers of pollen grains. This process results in a “rain” of pollen that falls over many types of environments. Pollen that ends up in lakebeds or peat bogs is the most likely to be preserved, but pollen may also become fossilized in arid conditions if the **soil** is acidic or cool. Scientists can develop a pollen chronology, or calendar, by noting which species of pollen were deposited earlier in time, that is, residue in deeper sediment or rock layers, than others. A pollen zone is a period of time in which a particular species is much more abundant than any other species of the time. In most cases, this also reveals much about the **climate** of the period, because most plants only thrive in specific climatic conditions. Changes in pollen zones can also indicate changes in human activities such as massive deforestation or new types of farming. Pastures for grazing livestock are distinguishable from fields of grain, so changes in the use of the land over time are recorded in the pollen history. The dates when areas of **North America** were first settled by immigrants can be determined to within a few years by looking for the introduction of ragweed pollen.

Pollen zones are translated into absolute dates by the use of radiocarbon dating. In addition, pollen dating provides relative dates beyond the limits of radiocarbon (40,000 years), and can be used in some places where radiocarbon dates are unobtainable.

Fluorine is found naturally in ground **water**. This water comes in contact with skeletal remains under ground. When this occurs, the fluorine in the water saturates the bone, changing the mineral composition. Over time, more and more fluorine incorporates itself into the bone. By comparing the relative amounts of fluorine composition of skeletal remains, one can determine whether the remains were buried at the same time. A bone with a higher fluorine composition has been buried for a longer period of time.

Absolute dating is the term used to describe any dating technique that tells how old a specimen is in years. These are generally analytical methods, and are carried out in a laboratory. Absolute dates are also relative dates, in that they tell which specimens are older or younger than others. Absolute dates must agree with dates from other relative methods in order to be valid.

This dating technique of amino acid racimization was first conducted by Hare and Mitterer in 1967, and was popular in the 1970s. It requires a much smaller sample than radiocarbon dating, and has a longer range, extending up to a few hundred thousand years. It has been used to date coprolites (fossilized feces) as well as fossil bones and shells. These types of specimens contain proteins embedded in a network of **minerals** such as calcium.

Amino acid racimization is based on the principle that amino acids (except glycine, a very simple amino acid) exist in two mirror image forms called stereoisomers. Living organisms (with the exception of some microbes) synthesize and incorporate only the L-form into proteins. This means that the ratio of the D-form to the L-form is zero (D/L=0). When these organisms die, the L-amino acids are slowly converted into D-amino acids in a process called racimization. This occurs because protons (H^+) are removed from the amino acids by acids or bases present in the burial environment. The protons are quickly replaced, but will return to either side of the amino acid, not necessarily to the side from which they came. This may form a D-amino acid instead of an L– amino acid. The reversible reaction eventually creates equal amounts of L– and D-forms (D/L=1.0).

The rate at which the reaction occurs is different for each amino acid; in addition, it depends upon the moisture, **temperature**, and **pH** of the postmortem conditions. The higher the temperature, the faster the reaction occurs, so the cooler the burial environment, the greater the dating range. The burial conditions are not always known, however, and can be difficult to estimate. For this reason, and because some of the amino acid racimization dates have disagreed with dates achieved by other methods, the technique is no longer widely used.

Cation-ratio dating is used to date rock surfaces such as stone artifacts and cliff and ground drawings. It can be used to obtain dates that would be unobtainable by more conventional methods such as radiocarbon dating. Scientists use cation-ratio dating to determine how long rock surfaces have been exposed. They do this by chemically analyzing the varnish that forms on these surfaces. The varnish contains cations, which are positively charged atoms or molecules. Different cations move throughout the environment at different rates, so the ratio of different cations to each other changes over time. Cation ratio dating relies on the principle that the cation ratio $(K^++Ca^{2+})/Ti^{4+}$ decreases with increasing age of a sample. By calibrating these ratios with dates obtained from rocks from a similar microenvironment, a minimum age for the varnish can be determined. This technique can only be applied to rocks from **desert** areas, where the varnish is most stable.

Although cation-ratio dating has been widely used, recent studies suggest it has potential errors. Many of the dates obtained with this method are inaccurate due to improper chemical analyses. In addition, the varnish may not actually be stable over long periods of time.

Thermoluminescence dating is very useful for determining the age of pottery. Electrons from **quartz** and other minerals in the pottery **clay** are bumped out of their normal positions (ground state) when the clay is exposed to radiation. This radiation may come from radioactive substances such as uranium,

Scientist using a spectrograph to determine the age of a sample. © *Roger Ressmeyer/Corbis. Reproduced by permission.*

present in the clay or burial medium, or from cosmic radiation. When the ceramic is heated to a very high temperature (over 932°F [500°C]), these electrons fall back to the ground state, emitting light in the process and resetting the "clock" to zero. The longer the radiation exposure, the more electrons get bumped into an excited state. With more electrons in an excited state, more light is emitted upon heating. The process of displacing electrons begins again after the object cools. Scientists can determine how many years have passed since a ceramic was fired by heating it in the laboratory and measuring how much light is given off. Thermoluminescence dating has the advantage of covering the time interval between radiocarbon and potassium-argon dating, or 40,000–200,000 years. In addition, it can be used to date materials that cannot be dated with these other two methods.

Optically stimulated luminescence (OSL) has only been used since 1984. It is very similar to thermoluminescence dating, both of which are considered "clock setting" techniques. Minerals found in sediments are sensitive to light. Electrons found in the sediment grains leave the ground state when exposed to light, called recombination. To determine the age of sediment, scientists expose grains to a known amount of light and compare these grains with the unknown sediment. This technique can be used to determine the age of unheated sediments less than 500,000 years old. A disadvantage to this technique is that in order to get accurate results, the sediment to be tested cannot be exposed to light (which would reset the "clock"), making sampling difficult.

The absolute dating method utilizing tree ring growth is known as dendrochronology. It is based on the fact that trees produce one growth ring each year. Narrow rings grow in cold and/or dry years, and wide rings grow in warm years with plenty of moisture. The rings form a distinctive pattern, which is the same for all members in a given species and geographical area. The patterns from trees of different ages (including ancient wood) are overlapped, forming a master pattern that can be used to date timbers thousands of years old with a resolution of one year. Timbers can be used to date buildings and archaeological sites. In addition, tree rings are used to date changes in the climate such as sudden cool or dry periods. Dendrochronology has a range of one to 10,000 years or more.

As previously mentioned, radioactive decay refers to the process in which a radioactive form of an element is converted into a decay product at a regular rate. Radioactive decay dating is not a single method of absolute dating but instead a group of related methods for absolute dating of samples.

Potassium-argon dating relies on the fact that when volcanic rocks are heated to extremely high temperatures, they release any argon gas trapped in them. As the rocks cool, argon-40 (^{40}Ar) begins to accumulate. Argon-40 is formed in the rocks by the radioactive decay of potassium-40 (^{40}K). The amount of ^{40}Ar formed is proportional to the decay rate (**half-life**) of ^{40}K, which is 1.3 billion years. In other words, it takes 1.3 billions years for half of the ^{40}K originally present to be converted into ^{40}Ar. This method is generally only applicable to rocks greater than three million years old, although with sensitive instruments, rocks several hundred thousand years old may be dated. The reason such old material is required is that it takes a very long time to accumulate enough ^{40}Ar to be measured accurately. Potassium-argon dating has been used to date volcanic layers above and below **fossils** and artifacts in east **Africa**.

Radiocarbon dating is used to date charcoal, wood, and other biological materials. The range of conventional radiocarbon dating is 30,000–40,000 years, but with sensitive instrumentation, this range can be extended to 70,000 years. Radiocarbon (^{14}C) is a radioactive form of the element **carbon**. It decays spontaneously into nitrogen-14 (^{14}N). Plants get most of their carbon from the air in the form of **carbon dioxide**, and animals get most of their carbon from plants (or from animals that eat plants). Relative to their atmospheric proportions, atoms of ^{14}C and of a non-radioactive form of carbon, ^{12}C, are equally likely to be incorporated into living organisms. While a plant or animal is alive, the ratio of ^{14}C/^{12}C in its body will be nearly the same as the ^{14}C/^{12}C ratio in the atmosphere. When the organism dies, however, its body stops incorporating new carbon. The ratio will then begin to change as the ^{14}C in the dead organism decays into ^{14}N. The rate at which this process occurs is called the half-life. This is the time required for half of the ^{14}C to decay into ^{14}N. The half-life of ^{14}C is 5,730 years. Scientists can estimate how many years have elapsed since an organism died by comparing the ^{14}C/^{12}C ratio in the remains with the ratio in the atmosphere. This allows them to determine how much ^{14}C has formed since the death of the organism.

One of the most familiar applications of radioactive dating is determining the age of fossilized remains, such as dinosaur bones. Radioactive dating is also used to authenticate the age of rare archaeological artifacts. Because items such as paper documents and cotton garments are produced from plants, they can be dated using radiocarbon dating. Without radioactive dating, a clever forgery might be indistinguishable from a real artifact. There are some limitations, however, to the use of this technique. Samples that were heated or irradiated at some time may yield by radioactive dating an age less than the true age of the object. Because of this limitation, other dating techniques are often used along with radioactive dating to ensure accuracy.

Accurate radiocarbon dating is that diagenic (after death) demands consideration regarding potential contamination of a specimen and a proper application of changes in the ^{14}C/^{12}C ratio in the atmosphere over time. ^{14}C levels can be measured in tree rings and used to correct for the ^{14}C/^{12}C ratio in the atmosphere at the time the organism died, and can even be used to calibrate some dates directly. Although the magnitude of change of the ^{14}C/^{12}C ratio sometimes stirs controversy, with proper calibration and correction, radiocarbon dating correlates well with other dating techniques and consistently proves to be an accurate dating technique—especially for Pleistocene and Holocene period analysis.

Uranium series dating techniques rely on the fact that radioactive uranium and thorium isotopes decay into a series of unstable, radioactive "daughter" isotopes; this process continues until a stable (non-radioactive) **lead** isotope is formed. The daughters have relatively short half-lives ranging from a few hundred thousand years down to only a few years. The "parent" isotopes have half-lives of several billion years. This provides a dating range for the different uranium series of a few thousand years to 500,000 years. Uranium series have been used to date uranium-rich rocks, deep-sea sediments, shells, bones, and teeth, and to calculate the ages of ancient lakebeds. The two types of uranium series dating techniques are daughter deficiency methods and daughter excess methods.

In daughter deficiency situations, the parent radioisotope is initially deposited by itself, without its daughter (the isotope into which it decays) present. Through time, the parent decays to the daughter until the two are in equilibrium (equal amounts of each). The age of the deposit may be determined by measuring how much of the daughter has formed, providing that neither isotope has entered or exited the deposit after its initial formation. Carbonates may be dated this way using, for example, the daughter/parent isotope pair protactinium-231/uranium-235 (^{231}Pa/^{235}U). Living mollusks and corals will only take up dissolved compounds such as isotopes of uranium, so they will contain no protactinium, which is insoluble. Protactinium-231 begins to accumulate via the decay of ^{235}U after the organism dies. Scientists can determine the age of the sample by measuring how much ^{231}Pa is present and calculating how long it would have taken that amount to form.

In the case of daughter excess, a larger amount of the daughter is initially deposited than the parent. Non-uranium daughters such as protactinium and thorium are insoluble, and precipitate out on the bottoms of bodies of water, forming daughter excesses in these sediments. Over time, the excess daughter disappears as it is converted back into the parent, and by measuring the extent to which this has occurred, scientists can date the sample. If the radioactive daughter is an isotope of uranium, it will dissolve in water, but to a different extent than the parent; the two are said to have different solubilities. For example, ^{234}U dissolves more readily in water than its parent, ^{238}U, so **lakes** and **oceans** contain an excess of this daughter isotope. This excess is transferred to organisms such as mollusks or corals, and is the basis of ^{234}U/^{238}U dating.

Some volcanic minerals and glasses, such as **obsidian**, contain uranium-238 (^{238}U). Over time, these substances become "scratched." The marks, called tracks, are the damage caused by the fission (splitting) of the uranium atoms. When an **atom** of ^{238}U splits, two "daughter" atoms rocket away from each other, leaving in their wake tracks in the material in which they are embedded. The rate at which this process occurs is proportional to the decay rate of ^{238}U. The decay rate is measured in terms of the half-life of the element, or the time it takes for half of the element to split into its daughter atoms. The half-life of ^{238}U is 4.47×10^9 years.

When the mineral or **glass** is heated, the tracks are erased in much the same way cut marks fade away from hard candy that is heated. This process sets the fission track clock to zero, and the number of tracks that then form are a measure of the amount of time that has passed since the heating event. Scientists are able to count the tracks in the sample with the aid of a powerful microscope. The sample must contain enough ^{238}U to create enough tracks to be counted, but not contain too much of the isotope, or there will be a jumble of tracks that cannot be distinguished for counting. One of the advantages of fission track dating is that it has an enormous dating range. Objects heated only a few decades ago may be dated if they contain relatively high levels of ^{238}U; conversely, some meteorites have been dated to over a billion years old with this method.

Although certain dating techniques are accurate only within certain age ranges, whenever possible, scientists attempt to use multiple methods to date specimens. **Correlation** of dates via different dating methods provides a highest degree of confidence in dating.

See also Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology

DAVIS, WILLIAM MORRIS (1850-1934)

American geologist

William Morris Davis was a geographer, meteorologist, and geologist who devised a relative method of determining the age of a river system. Davis' method of landscape analysis considered the cyclical nature of **erosion** and the subsequent uplift of the surrounding land in order to determine the age of the river in relation to its surroundings.

Davis was born in Philadelphia, Pennsylvania into the city's social elite. His grandmother was Lucretia Mott, the famous abolitionist. William Morris Davis bore the name of his uncle, a congressman. Davis spent many of his childhood summers in the farmlands of Pennsylvania, which instilled in him a deep interest in natural history. This interest spurred Davis to study at the Lawrence Scientific School of Harvard University. After his graduation in 1869, he pursued a master's degree in mining engineering, also at Harvard. Davis embarked on a tour of the mining districts of the Lake Superior region with Raphael Pumpelly during the summer of 1869. Later in the same summer, Davis helped Josiah Dwight Whitney conduct fieldwork in the Rocky Mountains. In 1870, Davis accompanied one of his former teachers, Benjamin Gould, to Argentina for the purpose of organizing an astronomical observatory. Davis remained in Cordoba for two and a half years assisting Gould with the observatory and undertaking meteorological work. Davis then returned to Philadelphia after experiencing differences with Gould.

Davis later became an instructor at Harvard, but initially struggled to interest his students. He commenced a lifelong career in research and writing in 1882. In the 1880s, Davis received notice for his work in **geology** and **meteorology**, but was internationally known for his research in **physical geography**. Davis turned out many articles on the Triassic formation of the Connecticut River Valley and on meteorological topics. In 1889, Davis wrote a paper on "The Rivers and Valleys of Pennsylvania." In this paper, Davis introduced the cycle for river system formations that was reiterated in many more of his works. Davis believed that running **water** is the single most important agent in creating landscapes. At the beginning of his erosion cycle, rivers are small, shallow streams, the result of imperfect drainage of the surrounding **topography**. With time, the streams carve out deeper channels, widen, and contributing tributaries form. These tributaries, in turn, bring in more and more water creating larger, more powerful waterways. Waterfalls are caused by the contrast of hardness of the rocks as they are worn back. Side-streams then form their own valleys and the valley slopes increase as more **soil** is carried downstream. At maturity, the river has a system of headwater branches that gnaw at the uplands, which in turn widen the rivers. The surrounding mountains then slowly erode over time. This erosion deposits a large amount of sediment into the rivers. This causes the rivers to become increasingly sluggish and the tributaries dwindle as the flow of water slows. The cycle then begins again when another episode of uplift rejuvenates the river systems. Davis, who was influenced by the English scientist Charles Darwin's organic evolutionary theories, determined the relative age of the river system by discerning its place in the erosion cycle and thus, proposed a cyclical nature to the **evolution** of the landscape.

Davis published the textbook, *Elementary Meteorology* (1894), which was widely used in colleges. Other relevant scientific literature published by Davis includes: *Elementary Physical Geography* (1902), *Geographical Essays* (1909), *The Lesser Antilles* (1926), and *The Coral Reef Problem* (1928). In *The Coral Reef Problem*, Davis endorsed both James Dwight Dana's and Darwin's belief that barriers such as atolls and reefs are the result from the slow subsidence of the ocean bottom under the upward growing formations of islands.

Davis was appointed Sturgis-Hooper Professor of geology at Harvard in 1898. He retained this position until his retirement in 1912. Davis founded the Association of American Geographers in 1904. He also played a major role in the Geological Society of America. In 1928, Davis, a widower, married his third wife and settled in Pasadena, California where he peacefully lived out his final years until his death in 1934.

See also Landscape evolution

DEBRIS FLOW

Debris flow is a process in which water-saturated masses of material ranging from **sand** grains to boulders move across low slopes. These flows range from gently flowing sand and **water** slurries to violently surging bouldery masses, and include events described as debris slides, debris torrents, mudflows, mudslides, earthflows, and lahars.

Observations have shown that debris flows often move in waves or surges, each wave consisting of a coarse-grained snout followed by a finer grained and more fluid tail. The consistency of flowing debris has been described as being similar to wet concrete, although water accounts for less than half of the debris flow volume. Debris flows typically have bulk densities almost identical to the water-saturated **regolith** or sediment from which they are derived. Clay- and silt-sized grains are generally very minor constituents.

Most debris flows begin as landslides or slumps. In order for a **landslide** to be mobilized into a debris flow, two conditions (in addition to initial landsliding) must be met. First, the debris mass must contain enough water to flow when agitated during sliding. Second, the gravitational potential energy possessed by the debris must be converted into enough internal kinetic energy to change the mode of movement from rigid block sliding to fluid flow throughout the debris mass. Landslides that mobilize into debris flows often occur along topographic concavities or hollows, which concentrate **groundwater** flow and contain thicker accumulations of regolith than surrounding ridges. Concentrated groundwater flow increases the wetness of regolith in hollows, making it particularly susceptible to destabilizing groundwater pressure increases during and immediately after rainstorms. Debris stops flowing when the internal kinetic energy drops below the level necessary to maintain fluid flow, commonly because the channel through which the debris flows flattens or widens.

Debris flows are also common after intense wildfires. Fires that spawn debris flows create a layer of water repellent (hydrophobic) **soil** a few millimeters below the ground surface. Hydrophobic soil impedes the infiltration of rainwater, mobilizing the overlying soil into small debris flows and forming a drainage network throughout the burned **area**. The small debris flows contribute sediment to nearby stream channels, which can then be mobilized into larger debris flows during heavy rainstorms. Debris flows can also begin when hot volcanic ash flows melt snow and **ice** or when **floods** incorporate large amounts of sediment, but these are rare occurrences relative to debris flows mobilized from landslides.

See also Catastrophic mass movements; Drainage basins and drainage patterns; Erosion; Mass movement; Mass wasting; Mud flow

DEEP SEA EXPLORATION

Deep ocean basins cover almost 70% of Earth's surface, and they contain 96% of the planet's life-sustaining **water**. The **oceans** support the **biosphere** by modulating global **climate** and hydrology, and are home to the marine organisms that form the diverse base of the global ecosystem. Geology's unifying paradigm, the theory of **plate tectonics**, arose from deep-sea discoveries of the 1950s and 1960s. The title of marine geologist Philip Kuenen's 1958 paper, "No Geology without Marine Geology," rings especially true with hindsight of late twentieth century advancements in the field of marine geology.

The nature of the seafloor was an unrevealed mystery until the mid-nineteenth century; scientists and artists alike envisioned the deep sea as a lifeless soup of placid water, contained in a bowl of static **rock**. By the late 1860s, however, controversial theories of the **origin of life** by **evolution** and the vastness of **geologic time** had created a climate of scientific curiosity and piqued a general interest in marine science. The Royal Society of London thus mounted an ambitious oceanographic expedition to augment a sparse collection of existing marine data that included Charles Darwin's observations during the voyage of the *Beagle* (1831–1836), a bathymetric map created by U.S. Navy Lt. Matthew Maury to aid installation of the first trans-Atlantic telegraph cables in 1858, and a few examples of deep marine life. The HMS *Challenger* expedition (1872–1876) covered almost 70,000 miles, and shipboard scientists collected hundreds of sediment samples, hydrographic measurements, and specimens of marine life. They also dredged **mafic basalt** from the seafloor, critical evidence that oceanic **crust** is compositionally different from continental crust, and took almost 500 soundings that revealed the depth and basic physiography of the ocean basins.

While the *Challenger* expedition provided critical data that led to rapid advances in marine biology and **oceanography**, the Victorian concept of a geologically inert seafloor persisted for another seventy years. German meteorologist, **Alfred Wegener**, proposed his **continental drift theory** in 1912, but the idea was generally discarded because of inadequate knowledge of seafloor geology. During the 1920s and 1930s, development of sonar echosounding and detection of seafloor **gravity** anomalies rapidly improved the accuracy of bathymetric maps. The technology and government funding that accompanied naval and submarine warfare during World War II, however, precipitated marine geology's age of discovery. Princeton geologist and naval officer, Harry H. Hess, collected bathymetric, gravity, and magnetic polarity data during transatlantic troop transfers, and went on to become a founder of modern marine geology.

The scientific infrastructure of oceanographic institutions, instruments, and vessels that arose following WWII led directly to the theory of plate tectonics. Lamont Geological Observatory of Columbia University geologists surveyed the ocean basins with newly-refined depth recorders in the early 1950s. They discovered the globe-encircling mid-ocean ridge system, and suggested that oceanic crust is created at these chains of submarine volcanoes. Geophysical surveys of the deep **ocean trenches**, and exploration in manned submersibles, including the U.S. Navy's *Trieste* and *Alvin*, suggested the complementary process of seafloor consumption at subduction zones, and the theory of plate tectonics was born. Plate tectonics became widely accepted in the late 1960s as further geophysical surveys of the ocean, seafloor sampling and drilling by the Deep Sea Drilling Project (DSDP), and continental geology all corroborated the theory.

The technology of deep sea exploration has advanced from twine and cannon ball soundings, to ocean surveys from **space** and robotic exploration of the deep ocean floor. Modern sonar instruments provide high-resolution, three-dimensional images of the seafloor. Seafloor sample collections compiled by the DSPD, its successor the international Ocean Drilling Program (ODP), and many other oceanographic institutions, provide rock and sediment data to augment geophysical images. Seismic reflection surveys allow marine stratigraphers and **petroleum** geologists to investigate strata and potential source rocks beneath the seabed.

Technology, fueled by scientific curiosity, has revealed the deep ocean as a dynamic geological environment. The discoveries of intricate ecosystems at mid-ocean volcanic vents and the unexpected diversity of marine life have revolutionized biological science. Just as marine geology held the keys to understanding earth history, marine science may also be the path to understanding Earth's future. **Ocean circulation and currents** control Earth's climate and hydrology, the continental margins are home to most of Earth's human population, and the techniques developed for deep sea exploration are often applicable to space exploration.

See also Bathymetric mapping; Mid-ocean ridges and rifts; RADAR and SONAR; Remote sensing; Seismology

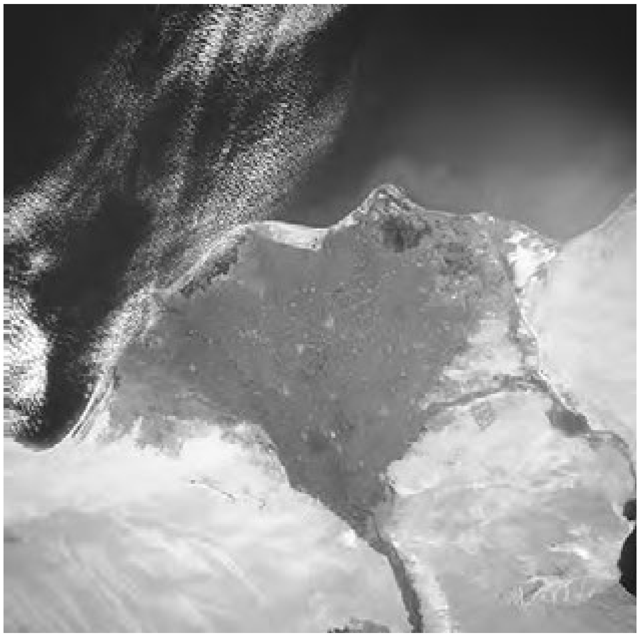
DEGREES, ARCMINUTES, AND ARCSECONDS • *see* LATITUDE AND LONGITUDE

DELTA

Deltas are complex depositional **landforms** that develop at the mouths of **rivers**. They are composed of sediment that is deposited as a river enters a standing body of **water** and loses forward momentum. Famous deltas include the Mississippi delta in Louisiana and the Nile delta in Egypt.

Every river flows, under the force of **gravity**, from its headwaters to its mouth. The mouth of a river is the location at which the river enters a standing body of water, such as a lake, sea, or the ocean. As the river enters standing water and the current is no longer confined to a channel, it spreads out, slows down, and eventually stops. The reduction in speed of the current causes the river to become unable to continue carrying suspended sediment. As sediment is deposited a series of smaller channels, called distributary channels, forms causing the shoreline to build out, or prograde. The landform created is the delta. In smaller rivers with weaker currents, forward momentum may cease almost immediately upon reaching the lake or ocean. This is especially true where the river empties into an **area** of strong wave action. In this case, no significant delta will be formed. Larger rivers, such as the Amazon, may be able to maintain some current for several miles out to sea, creating an extensive delta.

As a river reaches and enters a standing body of water, sediment is deposited according to grain size. The coarsest sediment, such as **sand**, is dropped first, closest to the mouth of the river. With progressive distance from the mouth, finer sediment including fine sand, silt, and **clay** is deposited. This results in a distinct sequence of layers, known as topsets, foresets, and bottomsets. The topsets, as the name implies, are the uppermost layer. They are comprised of the coarse sediment forming the area of the delta that is above sea level. The foresets include fine sand grading into silt and clay deposited in seaward sloping layers beyond the mouth. Bottomsets are made up of clay particles, carried furthest out to sea where they settle into horizontal layers. Although this sequence is deposited laterally with increasing distance from land, as a delta progrades the bottomsets are covered by new foresets, which are then covered by topsets as sediment builds up, and so on. The resultant coarsening up sequence is a distinguishing feature of deltaic deposits.



The Nile River delta, as seen from space. ***Corbis/NASA. Reproduced by permission.***

The sequence of topsets, foresets, and bottomsets provides an accurate picture of a simple delta system. Large marine deltas are often more complex, depending on whether the river, wave action, or the **tides** play the most important role. In stream-dominated deltas, fluvial deposition processes remain strongest, and distributary channels build far out to sea. These deltas are known as bird's foot deltas because of the appearance of the collection of channels extending into the sea. The Mississippi delta is probably the most famous example of a bird's foot delta. In wave-dominated deltas, distributary channels are not maintained for any great distance out to sea; rather, wave action reforms their sediment into **barrier islands** oriented perpendicular to the direction of flow. This type of delta is more compact, and shaped like a triangle. The Nile delta in Egypt is an example of a wave-dominated delta. Lastly, tide-dominated deltas are also compact, but broad tidal channels and sand bars form parallel to the tide direction. The Mekong delta in Vietnam is an example of a tide-dominated delta.

See also Alluvial system; Estuary; Landforms; Sedimentation

DEPOSITIONAL ENVIRONMENTS

Landscapes form and constantly change due to **weathering** and **sedimentation**. The **area** where sediment accumulates and is later buried by other sediment is known as its depositional environment. There are many large-scale, or regional, environments of deposition, as well as hundreds of smaller sub-environments within these regions. For example, **rivers** are regional depositional environments. Some span distances of hundreds of miles and contain a large number of sub-environments, such as channels, backswamps, **floodplains**, abandoned channels, and **sand** bars. These depositional sub-environments can also be thought of as depositional **landforms**, that is, landforms produced by deposition rather than **erosion**.

Depositional environments are often separated into three general types, or settings: terrestrial (on land), marginal marine (coastal), and marine (open ocean). Examples of each of these three regional depositional settings are as follows: terrestrial-alluvial fans, glacial valleys, **lakes**; marginal marine-beaches, deltas, estuaries, tidal mud and sand flats; marine-coral reefs, **abyssal plains**, and continental slope.

During deposition of sediments, physical structures form that are indicative of the conditions that created them. These are known as sedimentary structures. They may provide information about **water** depth, current speed, environmental setting (for example, marine versus fresh water) or a variety of other factors. Among the more common of these are: **bedding** planes, beds, channels, cross-beds, ripples, and mud cracks.

Bedding planes are the surfaces separating layers of sediment, or beds, in an outcrop of sediment or **rock**. The beds represent episodes of sedimentation, while the bedding planes usually represent interruptions in sedimentation, either erosion or simply a lack of deposition. Beds and bedding planes are the most common sedimentary structures.

Rivers flow in elongated depressions called channels. When river deposits are preserved in the sediment record (for example as part of a **delta** system), channels also are preserved. These channels appear in rock outcrops as narrow to broad, v- or u-shaped, “bellies” or depressions at the base of otherwise flat beds. Preserved channels are sometimes called cut-outs, because they “cut-out” part of the underlying bed.

Submerged bars along a coast or in a river form when water currents or waves transport large volumes of sand or gravel along the bottom. Similarly, **wind** currents form **dunes** from sand on a beach or a **desert**. While these depositional surface features, or **bedforms**, build up in size, they also migrate in the direction of water or wind flow. This is known as bar or dune migration. **Suspended load** or bedload material moves up the shallowly inclined, upwind or upcurrent (stoss) side and falls over the crest of the bedform to the steep, downwind or downcurrent (lee) side. If the bedform is cut perpendicular to its long axis (from the stoss to the lee side) one would observe inclined beds of sediment, called cross-beds, which are the preserved leeward faces of the bedform. In an outcrop, these cross-beds can often be seen stacked one atop another; some may be oriented in opposing directions, indicating a change in current or wind direction.

When a current or wave passes over sand or silt in shallow water, it forms ripples on the bottom. Ripples are actually just smaller scale versions of dunes or bars. Rows of ripples form perpendicular to the flow direction of the water. When formed by a current, these ripples are asymmetrical in cross-section and move downstream by erosion of sediment from the stoss side of the ripple, and deposition on the lee side. Wave-formed ripples on the ocean floor have a more symmetrical profile, because waves move sediments back and forth, not just in one direction. In an outcrop, ripples appear as very small cross-beds, known as cross-laminations, or simply as undulating bedding planes.

When water is trapped in a muddy pool that slowly dries up, the slow sedimentation of the **clay** particles forms a mud layer on the bottom of the pool. As the last of the water evaporates, the moist clay begins to dry up and crack, producing mud cracks as well as variably shaped mud chips known as mud crack polygons. Interpreting the character of any of the sedimentary structures discussed above (for example, ripples) would primarily provide information concerning the nature of the medium of transport. Mud cracks, preserved on the surface of a bed, give some idea of the nature of the depositional environment, specifically that it experienced alternating periods of wet and dry.

All clastic and organic sediments suffer one of two fates. Either they accumulate in a depositional environment, then get buried and lithified (turned to rock by compaction and cementation) to produce sedimentary rock, or they are re-exposed by erosion after burial, but before **lithification**, and go through one or more new cycles of weathering-erosion-transport-deposition-burial.

DESALINATION

Approximately 97% of Earth’s **water** is either sea water or brackish (salt water contained in inland bodies), both of which are undrinkable by humans. Desalination is the process of removing salt from seawater. Natural desalination occurs as a part of the **hydrologic cycle** as seawater evaporates. Manipulated desalinization—desalting, or saline water reclamation—is an energy expensive alternative to natural desalination.

Sea water contains 35,000 parts per million (ppm) (3.5% by weight) of dissolved solids, mostly sodium chloride, calcium and magnesium salts. Brackish water typically contains 5,000-10,000 ppm dissolved solids. To be consumable, or potable, water must contain less than 500 ppm dissolved solids. The method used to reach this level depends on the local water supply, the water needs of the community, and economics. Growing populations in arid or **desert** lands, contaminated **groundwater**, and sailors at sea all created the need for desalting techniques.

In the fourth century B.C., Aristotle related tales of Greek sailors desalting water using **evaporation** techniques. **Sand** filters were also used. Another technique used a wool wick to siphon the water. The salts were trapped in the wool. During the first century A.D., the Romans employed **clay** filters to trap salt. Distillation was widely used from the fourth century on—salt water was boiled and the steam collected in sponges. The first scientific paper on desalting was published by Arab chemists in the eighth century. By the 1500s, methods included filtering water through sand, distillation, and the use of white wax bowls to absorb the salt. The techniques have become more sophisticated, but distillation and filtering are still the primary methods of desalination for most of the world. The first desalination patent was granted in 1869, and in that same year, the first land-based steam distillation plant was established in Britain, to replenish the fresh water supplies of the ships at anchor in the harbor. A constant problem in such a process is scaling. When the water is heated over 160°F (71°C), the dissolved solids in water will precipitate as a crusty residue known as scale. The scale interferes with the transfer of heat in desalting machinery, greatly reducing the effectiveness. Today, the majority of desalting plants use a procedure known as multistage flash distillation to avoid scale. Lowering the pressure on the sea water allows it to boil at temperatures below 160°F (71°C), avoiding scaling. Some of the water evaporates, or flashes, during this low pressure boiling. The remaining water is now at a lower **temperature**, having lost some energy during the flashing. It is passed to the next stage at a lower temperature and pressure, where it flashes again. The condensate of the previous stage is piped through the water at the following stage to heat the water. The process is repeated many times. The water vapor is filtered to remove any remaining brine, then condensed and stored. Over 80% of land-based desalting plants are multistage flash distillation facilities.

A host of other desalinization processes have been developed. An increasingly popular process, reverse osmosis, essentially filters water at the molecular level, by forcing it through a membrane. The pressures required for brackish water range from 250 to 400 pounds per square inch (psi), while those for seawater are between 800 to 1,200 psi. The pressure required depends on the type of membrane used. Membranes have been steadily improving with the introduction of polymers. Membranes were formerly made of cellulose acetate, but today they are made from polyamide plastics. The polyamide membranes are more durable than those of cellulose acetate and require about half the pressure. Solar distillation is used in the subtropical regions of the world. Seawater is placed in a black tray and covered by a sloping sheet of **glass** or plastic. Sunlight passes through the cover. Water evaporates and then condenses on the cover. It runs down the cover and is collected. The salts are left behind in the trays.

Modern desalination technology allows use of desalinated water to supplement regular drinking water. The state of Florida, for example, is using dozens of reverse-osmotic plants to treat undrinkable brackish water and then mixing the treated water with the regular water supply. The intent is to extend the local water supply. Another approach is to make traditional methods, like distillation, more economically feasible.

See also Hydrologic cycle; Saltwater encroachment

DESERT AND DESERTIFICATION

Areas that receive less than 10 inches (25.4 cm) of rain a year are generally classified as deserts. Dry (arid) regions are usually found in **area** of high pressure (subtropical highs, leeward sides of mountains, etc.) associated with descending divergent air masses that are common between 30 degrees N and 30 degrees S **latitude**.

As a consequence of low moisture, desert vegetation is sparse and specifically adapted to conserve **water**. Deserts are areas of high **relief** (e.g., mesas, buttes, etc). Desert regions typically feature well-sorted sands, often found in various dune formations shaped by **sand** type, moisture content, and eoilian processes.

In desert areas, change usually occurs by some form of physical **weathering**. The wide diurnal **temperature** can make the modest amounts of moisture present powerful **weather** factors through continual **freezing** and thawing cycles that can result in micro-fracturing of **rock**. Winds often allow high levels of physical or frictional abrasion. Oxidation and other forms of chemical weathering produce familiar reddish dessert “varnish.”

Desertification refers to the gradual degradation of productive arid or semi-arid land into biologically unproductive land (e.g., a change of grassland to desert). The term desertification was first used by the French botanist Aubreville in 1949, to refer to the transformation of productive agricultural land into a desert-like condition.

However, the processes whereby arid lands are stripped of their productivity do not always result in the development of a desert. In some cases, desertification has been successfully reversed through careful land stewardship, and areas degraded by this process have been restored to a more productive condition. In the worst cases, however, semi-desert and desert lands can lose their sparse complement of plants and animals and become barren, gullied wasteland.

Desertification is sometimes caused by natural influences. This process has been ongoing for eons in some regions, in conjunction with long-term changes in climatic conditions, especially decreased **precipitation**. Until the twentieth century, humans were able to simply move their agricultural activity away from land rendered unusable by desertification. However, this strategy has been rendered less tenable by the immense population increase of humans during the past century, a change that has increased the attention paid to the degradation of once-productive drylands.

Desertification claimed major international attention in the 1970s. This resulted from an extended period of severe **drought** in the Sahel region during 1968 to 1973, affecting six African countries on the southern border of the Sahara Desert. Although international relief measures were undertaken, millions of livestock died during that prolonged drought, and thousands of people suffered or died of starvation.

Arid lands of parts of **North America** are among those severely affected by desertification; almost 90% of such habitats are considered to be moderately to severely desertified. The arid and semi-arid lands of the western and southwestern United States are highly vulnerable to this kind of damage. The perennial grasses and forbs that dominate arid-land vegetation can provide good forage for cattle, but if these animals are kept at too high a stocking density, they will overgraze and degrade the natural vegetation cover, contributing to **erosion** and desertification. In addition, excessive withdrawals of **groundwater** to irrigate crops and supply cities is exceeding the ability of the aquifers to replenish, resulting in a rapid decline in height of the **water table**. Moreover, the salts left behind on the **soil** surface after irrigation water evaporates results in land degradation through salinization, creating toxic conditions for crops.

Desertification is best regarded as a process of continuous ecosystem degradation, including damage to plants and animals, as well as to geophysical resources such as water and soil. Desertification is usually discussed in the context of dry regions and ecosystems, but it can also affect prairies, savannas, rain forest, and mountainous habitats. Such effects can range from minor to severe.

The physical characteristics of land undergoing desertification include the progressive loss of the natural, mature vegetation from the ecosystem; the loss of topsoil; increasing salinity of the soil that reduces crop yields and may produce a salty surface **crust** that hinders the seepage of water into the deeper soil; and an increasing number of gullies or sand **dunes** as the soil is eroded by **wind** action.

Among the natural forces of desertification are wind and water erosion of soil, long-term changes in rainfall patterns, and other changes in climatic conditions. The role of drought is variable and related in part to its duration; a prolonged drought accompanied by poor land management may be devastating, while a shorter drought might not be. As such, drought stresses the ecosystem without necessarily degrading it permanently. Rainfall similarly plays a variable role that depends on its duration, the seasonal pattern of its occurrence, and its spatial distribution. The list of human or cultural influences on desertification includes vegetation loss by overgrazing, the depletion of groundwater, surface **runoff** of rainwater, frequent burning, deforestation, the influence of invasive non-native species, physical compaction of the soil by livestock and vehicles, and damage by strip-mining.

Land management measures to combat desertification focus on improving sustainability and long-term productivity. It is not always possible to return a desertified area to its pre-desertified condition. As such, mitigating the effects of desertification is best achieved by converting the degraded ecosystem into a new state that can withstand cultural and climatic land-use pressures. Specific measures include developing a resilient vegetation cover of mixed trees, shrubs, and grasses suitable to local conditions. The soil must be protected against wind and water erosion, compaction, and salinization. Water diversions that excessively lower the water table must be reversed, and if possible new sources of water found for human and animal populations.

See also Adiabatic heating; Atmospheric circulation; Basin and range topography; Depositional environments; Desalination; Dune fields; Dust storms; Eolian processes; Erosion; Evaporation; Global warming; Hydrogeology; Hydrologic cycle; Landforms; Landscape evolution; Rate factors in geologic processes; Seasonal winds; Soil and soil horizons; Water table; Weathering and weathering series

DEVONIAN PERIOD

In **geologic time**, the Devonian Period, the fourth period of the **Paleozoic Era**, covers the time roughly 410 million years ago (mya) until 360 mya.

The Devonian Period spans three epochs. The Early Devonian Epoch is the most ancient, followed in sequence by the Middle Devonian Epoch, and the Late Devonian Epoch.

The Early Devonian Epoch is divided chronologically (from the most ancient to the most recent) into the Gedinnian, Siegenian, and Emsian stages. The Middle Devonian Epoch is divided chronologically (from the most ancient to the most recent) into the Eifelian and Givetian stages. The Late Devonian Epoch is divided chronologically (from the most ancient to the most recent) into the Frasnian and Famennian stages.

In terms of paleogeography (the study of the evolution of the continents from **supercontinents** and the establishment of geologic features), the Devonian Period featured continued cleavage of supercontinent landmass and fusion of plates into the supercontinent Laurasia and eventually the supercontinent Pangaea.

Differentiated by fossil remains and continental movements, the **Silurian Period** preceded the Devonian Period. The Devonian is followed in geologic time by the Carboniferous Period (360 mya to 286 mya). In many modern geological texts, especially those in the United States, the time of Carboniferous Period covered by two alternate geologic periods, the **Mississippian Period** (360 mya to 325 mya) and the **Pennsylvanian Period** (325 mya to 286 mya). A mass extinction marks the end of the Devonian Period. In accord with a mass extinction, many **fossils** dated to the Devonian Period are not found in Carboniferous Period (i.e., alternatively, Mississippian Period and Pennsylvanian Period) formations.

The Devonian Period marked a geologically active period. The North American and European continents—with more tropical climates due to more equatorial positions—drifted together. As a result, the two continents share a similar **fossil record** for the Devonian Period. Similar fossil finds dating to the Devonian Period are found in Germany, Canada, and the United States.

The fossil record indicates that it was during the Devonian Period (also termed the “Age of Fishes” because of the appearance of sharks and bony fishes) that amphibians and more terrestrial (land based) vertebrates evolved. Seed plants also appeared, continuing a diversification and development of botanical species, especially vascular plants. By the end of the Devonian Period, the first **forests** appeared.

There were a number of major impacts from large meteorites that date to the Devonian Period. Similar to the **K-T event**, many scientists argue that these impacts could have provided the environmental stresses that eliminated approximately 25% of Devonian Period species. Impact craters dating to the Devonian Period have been identified in modern China, Canada, Russia, and Sweden.

See also Archean; Cambrian Period; Cenozoic Era; Cretaceous Period; Dating methods; Eocene Epoch; Evolution, evidence of;

Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Tertiary Period; Triassic Period

DEW POINT

The dew point is that **temperature** below which the **water** vapor in a body of air cannot all remain vapor. When a body of air is cooled to its dew point or below, some fraction of its water vapor shifts from gaseous to liquid phase to form **fog** or cloud droplets. If a smooth surface is available, vapor condenses directly onto it as drops of water (dew).

The dew point of a body of air depends on its water vapor content and pressure. Increasing the fraction of water vapor in air (i.e., its relative **humidity**) raises its dew point; the water molecules are more crowded in humid air and thus more likely to coalesce into a liquid even at a relatively warm temperature. Decreasing the pressure of air lowers its dew point; lowering pressure (at constant temperature) increases the average distance between molecules and makes water vapor less likely to coalesce.

Air at ground level often deposits dew on objects at night as it cools. In this case, the dew point of the air remains approximately constant while its temperature drops. When the dew point is reached, dew forms. Ground mist and fog may also form under these conditions.

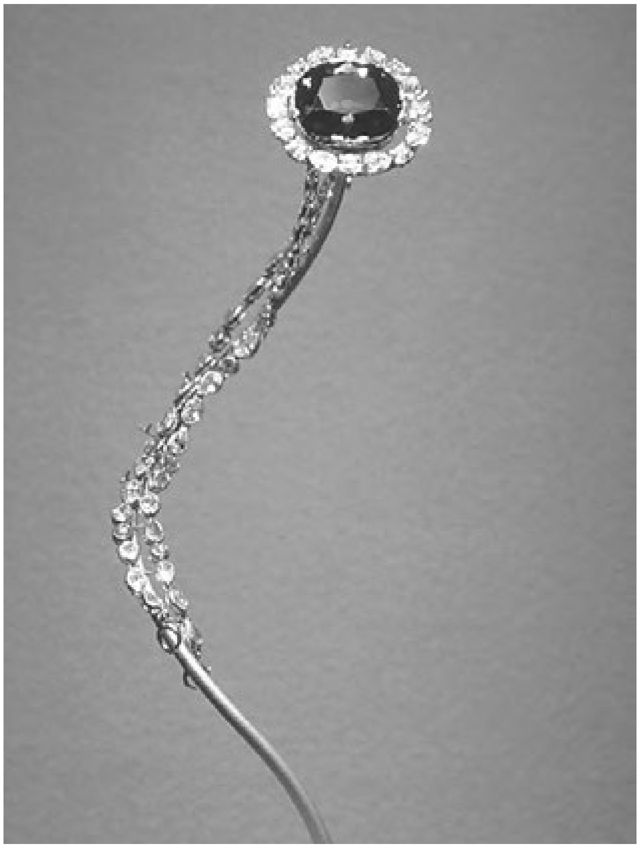
The dew point can be measured using a dew-point hygrometer. This instrument, invented in 1751, consists essentially of a **glass** with a thermometer inserted. The glass is filled with **ice** water and stirred. As the temperature of the glass drops, the air in contact with it is chilled; when it reaches its dew point, water condenses on the glass. The temperature at which **condensation** occurs is recorded as the dew point of the surrounding air.

If the dew point of a body of air is below 32°F (0°C), its water vapor will precipitate not as liquid water but as ice. In this case, the dew point is termed the frost point.

See also Atmospheric inversion layers; Atmospheric lapse rate; Cloud seeding; Clouds and cloud types; Evaporation; Precipitation; Weather forecasting methods; Weather forecasting

DIAMOND

Diamond is cubic native **carbon** with the same composition as **graphite**, but with different structure. It is the hardest mineral (10 on the **Mohs' scale**), with the highest refractive index of 2.417 among all transparent **minerals**, and has a high dispersion of 0.044. Diamonds are brittle. Under UV light, the diamond frequently exhibits luminescence with different colors. It has a density of 3.52 g/cm^3. The mass of diamonds is measured in carats; 1 carat=0.2 grams. Diamonds rarely exceed 15 carats. Diamonds are insoluble in acids and alkalis, and may burn in **oxygen** at high temperatures.


The Hope Diamond is one of the largest diamonds in the world. © *Richard T. Nowitz/Corbis. Reproduced by permission.*

Nitrogen is the main impurity found in diamonds, and influences its physical properties. Diamonds are divided into two types, with type I containing 0.001–0.23% nitrogen, and type II containing no nitrogen. If nitrogen exists as clusters in type I diamonds, it does not affect the color of the stone (type Ia), but if nitrogen substitutes carbon in the crystal lattice, it causes a yellow color (Ib). Stones of type II may not contain impurities (IIa), or may contain boron substituting carbon, producing a blue color and semiconductivity of the diamond.

Diamonds form only at extremely high pressure (over 45,000 atmospheres) and temperatures over 1100°C (2012°F) from liquid ultrabasic magmas or peridotites. Diamonds, therefore, form at great depths in the earth's **crust**. They are delivered to the surface by explosive volcanic phenomena with rapid cooling rates, which preserve the diamonds from transformation. This process happens in kimberlites (a peridotitic type of **breccia**), which constitutes the infill of diamond-bearing pipes. Also found with diamonds are **olivine**, serpentine, carbonates, pyroxenes, pyrope garnet, magnetite, hematite, graphite and ilmenite. Near the surface, kimberlite weathers, producing yellow loose mass called yellow ground, while deeper in the earth, it changes to more dense blue ground. Diamonds are extremely resistive to **corrosion**, so they can be fond in a variety of secondary deposits where they arrived after several cycles of **erosion** and **sedimentation** (alluvial diamond deposits, for example). Even in diamond-bearing **rock**, the diamond concentration is one gram in 8–30 tons of rock.

Most diamonds are used for technical purposes due to their hardness. Gem quality diamonds are found in over 20 counties, mainly in **Africa**. The biggest diamond producer is South Africa, followed by Russia. Usually, diamonds appear as isolated octahedron **crystals**. Sometimes they may have rounded corners and slightly curved faces. Microcrystalline diamonds with irregular or globular appearance are called Bort (or boart), while carbonado are roughly octahedral, cubic or rhombic dodecahedral, blackish, irregular microcrystalline aggregates. Both are valued for industrial applications because they are not as brittle as diamond crystals. Frequently, diamonds have inclusions of olivine, sulfides, chrome-diopside, chrome-spinels, zircon, rutile, disthene, biotite, pyrope garnet and ilmenite. Transparent crystals are usually colorless, but sometimes may have various yellowish tints. Rarely, diamonds may be bright yellow, blue, pale green, pink, violet, and even reddish. Some diamonds are covered by translucent skin with a stronger color. Diamonds become green and radioactive after neutron irradiation, and yellow after further heating. They become blue after irradiation with fast electrons. Diamonds have different hardnesses along their different faces. Diamonds from different deposits also have different hardnesses. This quality allows for the polishing of faceted diamonds by diamond powder.

Most diamond gems are faceted into brilliant cuts. Due to the high reflective index, all light passing through the face of such facetted diamonds is reflected back from the back facets, so light is not passing through the stone. This can be used as a diagnostic property, because most simulants (except cubic zirconia) do not have this property. Diamonds do have many simulants, including zircon, corundum, phenakite, tourmaline, topaz, beryl, **quartz**, scheelite, sphalerite, and also synthetic **gemstones** such as cubic zirconia, Yttrium-aluminum garnet, strontium titanate, rutile, spinel, and litium niobate. Diamonds have high thermal conductivity, which allows it to be readily and positively distinguished from all simulated gemstones. The most expensive diamonds are those with perfect structure and absolutely colorless or slightly bluish-white color. Yellow tint reduces the price of the diamond significantly. Bright colored diamonds are extremely rare, and have exceptionally high prices.

See also Gemstones

DIATOMS

Algae are a diverse group of simple, nucleated, plant-like aquatic organisms that are primary producers. Primary producers are able to utilize photosynthesis to create organic molecules from sunlight, **water**, and **carbon dioxide**. Ecologically vital, algae account for roughly half of photosynthetic production of organic material on Earth in both **freshwater** and marine environments. Algae exist either as single cells or as multicellular organizations. Diatoms are microscopic, single-celled algae that have intricate glass-like outer cell walls partially composed of **silicon**. Different species of diatom can be identified based upon the structure of these walls. Many diatom species are planktonic, suspended in the water column moving at the mercy of water currents. Others remain attached to submerged surfaces. One bucketful of water may contain millions of diatoms. Their abundance makes them important food sources in aquatic ecosystems. When diatoms die, their cell walls are left behind and sink to the bottom of bodies of water. Massive accumulations of diatom-rich sediments compact and solidify over long periods of time to form **rock** rich in fossilized diatoms that is mined for use in abrasives and filters.

Diatoms belong to the taxonomic phylum Bacillariophyta. There are approximately 10,000 known diatom species. Of all algae phyla, diatom species are the most numerous. The diatoms are single-celled, eukaryotic organisms, having genetic information sequestered into subcellular compartments called nuclei. This characteristic distinguishes the group from other single-celled photosynthetic aquatic organisms, like the blue-green algae that do not possess nuclei and are more closely related to bacteria. Diatoms also are distinct because they secrete complex outer cell walls, sometimes called skeletons. The skeleton of a diatom is properly referred to as a frustule.

Diatom frustules are composed of pure hydrated silica within a layer of organic, **carbon** containing material. Frustules are really comprised of two parts: an upper and lower frustule. The larger upper portion of the frustule is called the epitheca. The smaller lower piece is the hypotheca. The epitheca fits over the hypotheca as the lid fits over a shoebox. The singular algal diatom cell lives protected inside the frustule halves like a pair of shoes snuggled within a shoebox.

Frustules are ornate, having intricate designs delineated by patterns of holes or pores. The pores that perforate the frustules allow gases, nutrients, and metabolic waste products to be exchanged between the watery environment and the algal cell. The frustules themselves may exhibit bilateral symmetry or radial symmetry. Bilaterally symmetric diatoms are like human beings, having a single plane through which halves are mirror images of one another. Bilaterally symmetric diatoms are elongated. Radially symmetric diatom frustules have many mirror image planes. No matter which diameter is used to divide the cell into two halves, each half is a mirror image of the other. The combination of symmetry and perforation patterns of diatom frustules make them beautiful biological structures that also are useful in identifying different species. Because they are composed of silica, an inert material, diatom frustules remain well preserved over vast periods of time within geologic sediments.

Diatom frustules found in sedimentary rock are microfossils. Because they are so easily preserved, diatoms have an extensive **fossil record**. Specimens of diatom algae extend back to the **Cretaceous Period**, over 135 million years ago. Some kinds of rock are formed nearly entirely of fossilized diatom frustules. Considering the fact that they are microscopic organisms, the sheer numbers of diatoms required to produce rock of any thickness is staggering. Rock that has rich concentrations of diatom **fossils** is known as diatomaceous earth, or diatomite. Diatomaceous earth, existing today as large deposits of chalky white material, is mined for commercial use in abrasives and in filters. The fine abrasive quality of diatomite is useful in cleansers, like bathtub scrubbing powder. Also, many toothpaste products contain fossil diatoms. The fine **porosity** of frustules also makes refined diatomaceous earth useful in fine water filters, acting like microscopic sieves that catch very tiny particles suspended in solution.

Fossilized diatom collections also tell scientists a lot about the environmental conditions of past eras. It is known that diatom deposits can occur in layers that correspond to environmental cycles. Certain conditions favor mass deaths of diatoms. Over many years, changes in diatom deposition rates in sediments, then, are preserved as diatomite, providing clues about prehistoric climates.

Diatom cells within frustules contain chloroplasts, the organelles in which photosynthesis occurs. Chloroplasts contain chlorophyll, the pigment molecule that allows plants and other photosynthetic organisms to capture **solar energy** and convert it into usable chemical energy in the form of simple sugars. Because of this, and because they are extremely abundant occupants of freshwater and **saltwater** habitats, diatoms are among the most important microorganisms on Earth. Some estimates calculate diatoms as contributing 20–25% of all carbon fixation on Earth. Carbon fixation is a term describing the photosynthetic process of removing atmospheric carbon in the form of carbon dioxide and converting it to organic carbon in the form of sugar. Due to this, diatoms are essential components of aquatic food chains. They are a major food source for many microorganisms, aquatic animal larvae, and grazing animals like mollusks (snails). Diatoms are even found living on land. Some species can be found in moist **soil** or on mosses. Contributing to the abundance of diatoms is their primary mode of reproduction, simple asexual cell division. Diatoms divide asexually by mitosis. During division, diatoms construct new frustule cell walls. After a cell divides, the epitheca and hypotheca separate, one remaining with each new daughter cell. The two cells then produce a new hypotheca. Diatoms do reproduce sexually, but not with the same frequency.

See also Atmospheric chemistry; Depositional environments; Fossil record; Fossils and fossilization; Soil and soil horizons

DIKE

A dike is a formation of igneous **rock** that can form exposed vertical or linear ridges. Dikes are formed underground and are an intrusive plutonic rock formation. Intrusive formations form when upwelling **magma** cools and solidifies beneath the surface. As the magma rises it intrudes into the overlying **country rock** (older rock that is also termed “host” rock).

Dikes are vertical formations and thus form at a steep or often near right angle to the surface. Dikes are planar intrusions that, in contrast to horizontal sills, have a discordant form of contact with the host rock into which they intrude. A discordant contact is one that transverses or cuts across the established **bedding** planes of the country or host rock (e.g., at right angles to surrounding sedimentary bedding planes).

Dike texture varies from **aphanitic** (no visible mineral **crystals**) to phaneritic (visible mineral crystals). The texture is determined by the time needed for the upwelling magma to cool and solidify. Because dikes are vertical, gradients of textures can be established within the same dike (e.g., a change form aphanitic to phaneritic texture within the same dike. The longer the magma cooling time, the greater the extent and size of mineral crystal formation in the igneous rock comprising the dike. If, for example a dike—or a region of a dike—cools rapidly, the texture becomes uniform, smooth and without mineral crystals that are discernable upon visual inspection. If the magma in the dike cools over a long period of time, visible crystals form and the texture is described as phaneritic. Variation in the texture of dikes can also result from multiple intrusions of magma.

When exposed, dikes may form visible cliffs. In addition, dikes can form a network of underground passages for magma and when resistance to upward magma flow is encountered, a dike formation may give way to a horizontal **sill** intrusion.

Dikes can vary greatly in thickness across a range from a few inches to hundreds of yards. At the extreme, the great Dike of Zimbabwe extends more than 350 miles and has an average width of about six miles.

The formation of dikes often follows or reflects the fracturing of surrounding country rock. Accordingly, dikes often form in clumps or “swarms” and can occur in radial distributions about a deeper upwelling.

By definition, dikes form and cool underground. However, if the same form of magma upwelling reaches the surface, it results in a usually low viscosity volcanic **fissure** formation. Such formations are common in the Hawaiian islands (formed from an upwelling of a magmatic “hot spot”) and Iceland (formed as part of the magma upwelling associated with the Mid-Atlantic Ridge and in other areas of volcanic activity.

The search for such cliff formations is an important part of extraterrestrial studies conducted by the Mars Global Surveyor and probes sent to explore the moons of Jupiter. Identification of dike formations provide easily visible evidence of past volcanic activity, **mantle plumes**, and other forms of plate tectonic activity.

See also Igneous rocks; Pluton and plutonic bodies; Stratigraphy; Volcanic eruptions; Volcano

DIP • *see* STRIKE AND DIP

DISINTEGRATION, AGENTS OF • *see* WEATHERING AND WEATHERING SERIES

DIURNAL CYCLES

Diurnal cycles refer to patterns within about a 24-hour period that typically reoccur each day. Most daily cycles are caused by the **rotation** of the earth, which spins once around its axis about every 24 hours. The term diurnal comes from the Latin word *diurnus,* meaning daily. Diurnal cycles such as **temperature** diurnal cycles, diurnal **tides**, and solar diurnal cycles affect global processes.

A temperature diurnal cycle is composed of the daily rise and fall of temperatures, called the daily march of temperature. The daily rotation of the earth causes the progression of daytime and nighttime, thus controlling the air temperature. The daily maximum temperature occurs between the hours of 2 P.M. and 5 P.M. and then continually decreases until sunrise the next day. The angle of the **Sun** to the surface of the earth increases until around noon when the angle is the largest. The intensity of the Sun increases with the Sun's angle, so that the Sun is most intense around noon. However, there is a time difference between the daily maximum temperature and the maximum intensity of the Sun, called the lag of the maximum. This discrepancy occurs because air is heated predominantly by reradiating energy from Earth's surface. Although the Sun's intensity decreases after 12 P.M., the energy trapped within the earth's surface continues to increase into the afternoon and supplies heat to the earth's atmosphere. The reradiating energy lost from the earth must surpass the incoming **solar energy** in order for the air temperature to cool.

Diurnal tides are the product of one low tide and one high tide occurring roughly within a 24-hour period. Tides in general result from the relationship of the earth's gravitational attraction to the **Moon** and Sun. Additionally, the motion of the earth and Moon as well as the geometric relationship of the earth's location to both the Moon and Sun affects the tides. More specifically, the tilted axis of the earth in relation to the plane of the Moon plays an important role in creating diurnal tides. Typically, diurnal tides are weak tides that occur when the Moon is furthest from the equator. Diurnal tides occur in the northern part of the **Gulf of Mexico** and Southeast **Asia**.

The earth experiences varying hours of daylight due to the solar diurnal cycle. Solar diurnal cycles occur because the earth's axis is tilted 23.5 degrees and is always pointed towards the North Star, Polaris. The tilt of the earth in conjunction with the earth's rotation around the Sun affects the amount of sunlight the Earth receives at any location on Earth.

On March 21 or 22, the vernal equinox occurs where every location on Earth experiences exactly 12 hours of daylight. On this first day of spring, the Sun rises in the east and sets in the west. After the vernal equinox occurs, the Sun shifts north with each day until the day of the summer solstice on June 21 or 22. On this first day of summer, the Sun is as far north as possible and the Northern Hemisphere experiences its longest day of the year, while the Southern Hemisphere experiences its shortest day of the year. Over the next three months, the Sun moves progressively south and the days begin to get shorter in the Northern Hemisphere. On the day of the autumnal equinox, for the second time a year, the Sun rises due east and sets due west. On this first day of autumn, September 21 or 22, there are exactly 12 hours of daylight everywhere on Earth. After the autumnal equinox, the Sun continues to move south with each day and there continues to be less daylight with each passing day in the Northern Hemisphere until the winter solstice. On this first day of winter, December 21 or 22, the Sun has shifted as far south as possible and the Northern Hemisphere experiences its shortest day of the year while the Southern Hemisphere experiences its longest day of the year.

See also Earth (planet)

DIVERGENT PLATE BOUNDARY

In terms of **plate tectonics**, divergent boundaries are areas under tension where **lithospheric plates** are pushed apart by **magma** upwelling from the mantle. Lithospheric plates are regions of Earth's **crust** and upper mantle that are fractured into plates that move across a deeper plasticine mantle. At divergent boundaries, lithospheric plates move apart and crust is created.

Earth's crust is fractured into approximately 20 lithospheric plates. Each lithospheric plate is composed of a layer of oceanic crust or continental crust superficial to an outer layer of the mantle. Oceanic crust comprises the outer layer of the **lithosphere** lying beneath the **oceans**. Oceanic crust is composed of high-density rocks, such as **olivine** and **basalt**. Continental crust comprises the outer layer of the lithospheric plates containing the existing continents and some undersea features near the continents. Continental crust is composed of lower density rocks such as **granite** and **andesite**. New oceanic crust is created at divergent boundaries that are sites of **sea-floor spreading**.

At divergent boundaries, upwelling of magma along **mid-ocean ridges** (e.g., Mid-Atlantic Ridge) creates the tensional forces that drive the lithospheric plates apart.

Although initially formed from convection hot spots in the **asthenosphere**, rift valleys (e.g., Rift Valley of **Africa**) can fuse or interconnect to form zones of divergence that ultimately can fracture the lithospheric plate.

Containing both crust and the upper region of the mantle, lithospheric plates are approximately 60 miles (approximately 100 km) thick. Lithospheric plates may contain various combinations of oceanic and continental crust in mutually exclusive sections (i.e., the outermost layer is either continental or oceanic crust, but not both). Lithospheric plates move on top of the asthenosphere (the outer plastically deforming region of Earth's mantle).

Divergent plate boundaries are, of course, three-dimensional. Because Earth is an oblate sphere, lithospheric plates are not flat, but are curved and fractured into curved sections akin to the peeled sections of an orange. Divergent movement of lithospheric plates can best be conceptualized by the movement apart of those peeled sections over a curved surface (e.g., over a ball).

At divergent boundaries, tensional forces dominate the interaction between plates.

Because Earth's diameter remains constant, there is no net creation or destruction of lithospheric plates and so the amount of crust created at divergent boundaries is balanced by an equal destruction or uplifting of crust at convergent lithospheric plate boundaries.

Evidence of symmetrical bands of **rock** with similar ages located on either side of divergent boundaries offer important evidence in support of plate tectonic theory. In addition, similar fossil and magnetic bands also exist in equidistant bands on either side of a divergent boundary.

See also Convergent plate boundary; Dating methods; Earth, interior structure; Fossil record; Fossils and fossilization; Geologic time; Hawaiian island formation; Mapping techniques; Mid-ocean ridges and rifts; Mohorovicic discontinuity (Moho); Rifting and rift valleys; Subduction zone

DOLOMITE

The term dolomite is used both for the mineral dolomite (calcium magnesium carbonate [$CaMg(CO_3)_2$]) and for the **rock** dolomite, which consists mostly of the mineral dolomite. Dolomite rock is sometimes termed dolostone to distinguish it from the mineral dolomite, but the more confusing terminology is the more prevalent. Dolomite rock is formed from **limestone** (which is mostly calcite, i.e., calcium carbonate [$CaCO_3$]) by the replacement of about half of the limestone's calcium ions by magnesium ions. Because of its close relationship to limestone, dolomite is sometimes categorized as a type of limestone.

Limestone forms primarily in shallow **seas** and coastal waters where shelled marine organisms—crustaceans, mollusks, bivalves, and the like—proliferate. The shells of such creatures consist essentially of calcite. They accumulate on the sea floor in thick beds and are transformed into limestone over time. Some limestone is further transformed to dolomite by processes only partly understood. These various processes are lumped under the term dolomitization. The essential feature of all dolomitization processes is the importation of magnesium ions by **water**. These take up residence in the crystal structure of the limestone and convert it to dolomite.

Dolomites often occur in association with limestone, **gypsum**, and other rocks formed by shallow seas. Dolomite beds one or more meters thick are often sandwiched between similarly thick limestone beds. Dolomite and limestone are difficult to tell apart visually; a common field technique for distinguishing them is to drip hydrochloric acid (a hydrous solution of HCl) onto a hand sample. In response, limestone froths vigorously and dolomite weakly.

Metamorphosed limestone becomes calcite **marble**; metamorphosed dolomite becomes dolomitic marble. Dolomitic marble can be converted to calcite marble by dedolomitization, that is, the **leaching** out of magnesium.

Dolomites are used as magnesium ores, as a source of pharmaceutical magnesia (MgO), and as a flux—aid to the removal of impurities—in metal refining.

See also Fossils and fossilization; Field methods in geology; Industrial minerals

DOUGLAS SEA SCALE

The Douglas Sea Scale was devised by the English Admiral H.P. Douglas in 1917, while he was head of the British Meteorological Navy Service. Its purpose is to estimate the sea's roughness for navigation. The Douglas Scale consists of two codes, one for estimating the state of the sea (fresh waves attributable to local **wind** conditions), the other for describing sea swell (large rolling waves attributable to previous or distant winds).

The Douglas Sea Scale is expressed in one of 10 degrees.

- Degree 0—no measurable wave height, calm sea
- Degree 1—waves >10 cm., rippled sea
- Degree 2—waves 10–50 cm., smooth sea
- Degree 3—waves 0.5–1.25 m., slight sea
- Degree 4—waves 1.25–2.5 m., moderate sea
- Degree 5—waves 2.5–4 m., rough sea
- Degree 6—waves 4–6 m., very rough sea
- Degree 7—waves 6–9 m., high sea
- Degree 8—waves 9–14 m., very high sea
- Degree 9—waves >14 m., phenomenal sea

It was difficult to relate the existing wind scale designed by Sir Frances Beaufort in 1805 to a ship's features, especially as sails were replaced with the rigid structures of powered ships. The Douglas Sea Scale standardized the many variations being used by ship captains from many nations.

See also Beaufort wind scale; Wave motions

DOUGLASS, ANDREW ELLICOTT (1867-1962)

American astronomer and archaeologist

Andrew E. Douglass invented and named dendrochronology, the technique of counting and studying the rings in tree trunks to determine not only the ages of trees, but also the past climatological, geological, agricultural, social, and economic conditions of the local **area**.

Born in Windsor, Vermont, on July 5, 1867, Douglass received his bachelor's degree with honors in 1889 from Trinity College in Hartford, Connecticut. After working five years for the Harvard University Observatory, including an expedition to Arequippa, Peru, from 1891 to 1893 to establish Harvard's Southern Hemisphere Observatory, he accepted the offer of astronomer Percival Lowell (1855–1916) to build an observatory in the American Southwest. They founded Lowell Observatory in 1894 by erecting an 18-inch **telescope** on a mesa outside Flagstaff, Arizona. Lowell was preoccupied with Mars, and some historians argue that Lowell may have skewed Douglass' data in order to support his theories of Martian life and civilization. The two scientists' increasingly hostile disagreements about the proper use of data led Lowell to fire Douglass in 1901.

Douglass then taught school in the Flagstaff area, won an election for probate judge, and around 1904, began to note the connection between tree rings and solar cycles. In 1906, he

This scene from the movie "The Perfect Storm" shows an example of Degree 9 waves, according to the Douglas sea scale. Fortunately, such waves are rare. *The Kobal Collection. Reproduced by permission.*

moved to Tucson and joined the **astronomy** faculty of the University of Arizona. Increasingly interested in the possibility of using tree rings for archaeological dating, he concentrated his research on the ponderosa pine, the Douglas fir, and, in collaboration with Ellsworth Huntington (1876–1947), the giant sequoia. Beginning in 1909 his work received support from Clark Wissler (1870–1947) of the American Museum of Natural History in New York City and philanthropist Archer Milton Huntington (1870–1955). By the second decade of the twentieth century, dendrochronology was widely recognized as an important scientific insight.

After convincing Lavinia Steward (d. 1917) to found a new observatory at the University of Arizona with a bequest of $60,000 from the estate of her late husband, Henry B. Steward (d. 1902), Douglass became the first director of Steward Observatory in 1916. Its 36-inch reflecting telescope, one of the first in the nation, became operational in 1922 and the facility was dedicated in 1923.

Douglass retired from the observatory in 1937, but served the University of Arizona from 1937 until 1958 as the founding director of the Laboratory of Tree-Ring Research. He continued actively engaging in dendrochronological studies until within two years of his death in Tucson on March 20, 1962. His manuscripts and notes, held by the University of Arizona Library Special Collections, reveal an extraordinarily precise, flexible, and meticulous scientist.

See also Archeological mapping; Dating methods; Precipitation; Solar energy; Sun; Weathering and weathering series

DRAAS • *see* DUNE FIELDS

DRAINAGE BASINS AND DRAINAGE PATTERNS

A drainage basin is the **area** that encompasses all the land from which **water** flows into a particular stream or river. Stream is a synonym of river, and although typically something called a stream is smaller than a river, here, any flowing body of water in a clearly defined channel will be called a stream. The size of a drainage basin can vary from being as small as a few square miles or kilometers to as large as part of a continent. An example of a divide is the **continental divide** of **North America**, which separates streams that ultimately empty into one ocean (the Pacific Ocean) from those that ultimately empty into another (the **Gulf of Mexico**). The smallest streams in any particular area are called first order streams, and the land from which water flows into a particular first order stream is called a first order drainage basin. First order streams flow into second order streams, and each second order stream has its own second order drainage basin. There is no limit to how high an order a stream may be.

The drainage pattern that streams in a drainage basin trace out, visible in aerial photographs or even from the window of an airliner, can provide a lot of information about the type of terrain that the streams flow over. The dendritic drainage pattern of streams resembles the veins of a leaf, or the structure of a tree. It typically develops in areas with homogenous or flat-lying rocks that provide no preferred direction to the development of stream channels. Streams that flow over the flat-lying **rock** units of the American Midwest often display this type of drainage pattern. An annular drainage pattern forms when layers of rock are uplifted into a dome or downwarped into a basin, and the stream channels preferentially follow the weakest concentric beds of rock. A radial drainage pattern develops where there is a central highpoint, such as an isolated volcanic peak. The streams all flow away from the highest point. Fractures in massive rock such as **granite** can produce a drainage pattern in which the streams have many right-angle turns, and this is called rectangular drainage. When layered rock units are folded or tilted up, lower-order streams that flow into larger streams tend to be straight and follow weaker beds of rock. This trellis drainage pattern is common in the Appalachian Mountains of the United States. Centripetal drainage is found where streams flow into the center of a depression such as a basin or crater. Deranged drainage forms on terrain that is freshly exposed, and where the streams have not had a chance to develop in response to underlying geologic structure or **bedrock**. Finally, parallel drainage tends to develop in areas of massive rock with a uniform slope, where all the streams tend to flow in the same direction.

See also Avalanche; Delta; Drainage calculations and engineering; Hydrogeology; Runoff

DRAINAGE CALCULATIONS AND ENGINEERING

The design of hydraulic structures from small culverts to large dams requires engineers to calculate the amount of **water** that will flow through the channel along which the structure is built. The rate of flow through a stream channel, or discharge, is measured using units of cubic feet per second for engineering projects in the United States, and in units of cubic meters per second in other countries.

Engineers are often challenged when attempting to calculate how much drainage a particular area will need. Nature, however, has proven difficult to predict. ***AP/Wide World. Reproduced by permission.***

In many cases, knowledge of the maximum rate of flow that is likely to occur in a channel is required. For example, an engineer may wish to ensure that a bridge will be built high enough to allow passage of the largest flood likely to occur during the useful life of the bridge. If the maximum discharge is known or can be estimated, then it is a simple matter to calculate the height to which water will rise in a given channel. This is can be accomplished using Manning's equation, which relates discharge to the channel cross-sectional **area** and perimeter, the channel slope, and channel roughness.

The relationship between **precipitation** and the discharge of nearby streams is controlled by many factors. These include rainfall intensity and duration, drainage basin area, **topography**, **soil** and **bedrock** type, land use, vegetative ground cover, and the amount of precipitation in the days or weeks before a storm. Because it is difficult to incorporate this degree of complexity into mathematical models reflecting the **physics** of precipitation and stream discharges, let alone forecast the **weather**, probabilistic approaches based on the historical frequency of peak discharges are commonly used in engineering calculations. For **drainage basins** in which a long record of maximum annual discharges is available, discharges can be ranked from largest to smallest. Standard formulae are then used to estimate the probability that a given discharge will be exceeded over a specified period of time. A 100-year flood, for example, is one with a discharge that is inferred to occur on average once every 100 years. The term "on average" is an important qualifier because it means that a 100-year flood may occur more or less often than once every 100 years.

The probability that a discharge of given magnitude will occur over a specified time period is estimated using a binomial probability distribution. The binomial distribution can be used to show that there is a 37% chance that no 100-year flood will occur during any given 100-year period. Similarly, there is an 18% probability that two 100-year **floods** will occur during any given 100-year period. This logic can be extended to determine with a specified level of certainty the largest discharge that is likely to occur during the useful life of a hydraulic structure. An engineer designing a flood conveyance channel large enough to handle the discharge with a 90% likelihood of not being exceeded during the 50 year useful life of the channel would not use the discharge of the 50-year flood, but rather the discharge of the 475-year flood.

In some cases, particularly in small or remote drainage basins, flood discharge records may not be available and other methods must be used. One of the simplest techniques is the rational method, which relates peak stream discharge to the product of drainage basin area, rainfall intensity, and a coefficient representing the type of land use or ground cover in the drainage basin. In the United States, the rational method uses units of inches per hour for rainfall intensity and acres for drainage basin area. Values for the coefficient are tabulated in engineering reference books, and range from 0.05 for grassy areas with sandy soil to 0.95 for paved areas. The values can be averaged in cases where there are several different land uses within a drainage basin.

More sophisticated techniques can be used when the change in discharge as a function of time, as opposed to simply the peak discharge, is an important factor in design.

See also Drainage basins and drainage patterns; Hydrologic cycle; Stream valleys, channels, and floodplains

DROUGHT

Drought is a temporary hazard of nature occurring from a lack of **precipitation** over an extended period of time. Drought differs from aridity, a permanent feature of **climate** restricted to regions of low rainfall. Rainfall deficiencies caused by a drought create a severe hydrologic imbalance resulting in considerable **water** shortages.

The beginning of a drought is typically determined by comparing the current meteorological situation to an average based on a 30-year period of record. This "operational" definition of drought allows meteorologists to analyze the frequency, severity, and duration of the aberration for any given historical period and aides in the development of response and mitigation strategies.

The agricultural sector is usually the first to be affected by dryness, since crops are heavily dependent on stored soil water. ***Jim Sugar. Jim Sugar Photgraphy/Corbis-Bettmann. Reproduced by permission.***

Characteristics of drought are highly variable from region to region, depending on atmospheric factors such as **temperature**, **wind**, relative **humidity**, and amount of sunshine and cloud cover. High temperatures and lots of sunshine can increase **evaporation** and transpiration to such an extreme that frequent rainfall is incapable of restoring the loss. Meteorological definitions of drought, therefore, may deviate from operational definitions and are usually based on the length of the dry period and the degree of dryness in comparison to the daily average.

Drought is more than a physical phenomena; an extended period of dryness can have a significant socioeconomic impact. Drought presents the most serious physical hazard to crops in nearly all regions of the world. The agricultural sector is usually the first to be affected by dryness, since crops are heavily dependent on stored **soil** water. In addition to a decline in agricultural products, a shortfall in the water supply can disrupt availability of other economic goods such as hydroelectric power. The 1988–89 Uruguay drought resulted in a significant decline of hydroelectric power because the dryness disrupted the streamflows needed for production.

See also Hydrologic cycle

DRUMLINS • *see* GLACIAL LANDFORMS

DRY AIR • *see* HUMIDITY

DUNE FIELDS

Dune fields are large features of eolian or arid environments. They are associated with hot **climate** deserts such as the Sahara. Dune fields are not, however, exclusively restricted to these types of environments. Many dune fields are found in temperate climates where the processes of aridity in an arid climate combine to form **dunes**, but at a much slower rate than hot, arid climates.

The basic processes that contribute to dune formation are straightforward. It is the range of minute geological processes that generates controversy in dune research. When a geographical region experiences prolonged **drought** accompanied by high **evaporation** rates, the soils lose vegetation. Plant roots secure loose particles that make up soils. When **wind** sweeps across the barren **soil**, the first stages of dune and **desert** formation occur.

Wind is an excellent agent for separating grains sizes and weights in soils. Although not as effective as **water** for transporting sediments, it is responsible for a tremendous amount of silt and **sand** relocation around the planet. Wind picks up lighter and smaller particles, such as the types of **clay minerals**, and moves them far away from their source. Atmospheric dust can circulate the globe and may stay in the air for days, weeks, and even years. It later settles in all types of places, even the polar areas.

Unlike these lightweight minerals, heavier minerals such as **quartz** remain in their original spot and begin to accumulate. They are rolled around by wind but not removed. The rolling makes the grains smooth and of the type more commonly associated with dunes than with water deposits. The grains are typically light in color and are what make dune fields light beige to white in hue.

Dune fields are active regions of moving sands that form characteristic shapes including the well-known crescent dune. The macro and microscopic movement of sand particles is an **area** still being intensively studied. One method of particle movement is called **saltation**. This is a process in which the wind is not strong enough to pick up the grains, but, instead, moves the grains along the ground in a hopping and rolling fashion. As the grains climb up the faces of dunes facing the wind, they reach the crest where they bounce off the top. Movies of this action have been carefully studied. This airborne motion of grain movement can be seen as wisps of sand curling from the tops of dunes much like the snows blowing from mountain tops.

The sediments that accumulate on the windward slope are called topset deposits. When they reach the crest, they form an unstable and temporary surface called the brink. When enough sediments are captured on the brink they eventually tumble over the edge onto the slipface. This motion provides the advancement of the dune as it migrates in the direction of the wind. A temporary halt in dune movement can make a thin layer of sediments that become slightly bonded to one another. This layer becomes visible in side view and is even more recognizable in ancient deposits.

The sequence of dune formation has been widely studied. Increased or decreased wind strength is the force that makes the wide variety of dune shapes. This has led to a wide variety of terms used to describe dunes, dune fields, and other structures. Barchan dunes are the traditional crescent shaped dunes where the tips lie pointing away from the direction of the wind. Parabolic dunes are also crescent-shaped, but in this case, the tips lie facing the wind. Star dunes represent a dune formed from wind that blows from a variety of directions. Draas is an antiquated term used to describe huge dune fields that are often only observable from **space**. An erg is a region in the Sahara that is occupied by deep and complex sand dunes. Size is one of the factors that distinguish ergs from draas.

Dune fields themselves are complex environments. Within the field, there are many microenvironments that lie between the dunes and at the bottom of dune valleys. Moisture may even accumulate and form small ponds. Scientists continue to study dunes and dune fields. They are one of the least understood structures in **geology** because of the difficulty in studying them. However, dune fields occur over a significant portion of Earth's surface and certainly command more attention.

See also Beach and shoreline dynamics; Desert and desertification; Seawalls and beach erosion

DUNES

Dunes are well-sorted deposits of materials by **wind** or **water** that take on a characteristic shape and that retain that general shape as material is further transported by wind or water. **Desert** dunes classifications are based upon shape include barchan dunes, relic dunes, transverse dunes, lineal dunes, and blount (parabolic) dunes. Dunes formed by wind are common in desert areas and dunes formed by water are common in coastal areas. Dunes can also form on the bottom of flowing water (e.g., stream and river beds).

When water is the depositing and shaping agent, dunes are a bedform that are created by **saltation** and deposition of particles unable to be carried in suspension. Similar in shape to ripples—but much larger in size—dunes erode on the upstream side and extend via deposition the downstream or downslope side.

Regardless of whether deposited by wind or water, dunes themselves move or migrate much more slowly than any individual deposition particle.

In desert regions, dune shape is dependent upon a number of factors including the type of **sand**, the moisture content of the sand, and the direction and strength of the prevailing wind pattern. Barchan dunes are crescent-shaped small dunes with the terminal points of the crescent pointed downwind (on the lee side of the prevailing wind). Transverse dunes are long narrow dunes (a dune line) formed at right angles to the prevailing wind pattern. Transverse dunes may form from the fusion of individual barchan dunes.

Blount or parabolic dunes may form in regions of higher moisture content where there is sufficient vegetation to retard the migration of sand. Blount dunes take the mirror image shape of barchan dunes—they are crescent-shaped, but the terminal points of the crescent point windward (into the direction of the prevailing winds). Lineal dunes form parallel to prevailing wind patterns. Lineal dunes may be become the dominant **relief** feature and dunes may measure several hundred yards or meters high and extend for more than 50 miles (80 km).

Desert dunes migrate downwind from prevailing winds. Relic dunes form as migration slows and vegetation forms on a dune.

Ergs are "dune seas" ("erg" derives from Arabic) or large complexes of dunes. Very large (generally over 100 meters high and at least a kilometer long) complexes of dunes form a drass. Globally, **dune fields** and **seas** are common between 20° to 40° N, and 20° to 40° S latitudes.

In contrast to well-sorted dunes, a loess is another form of sedimentary, wind-driven deposit usually associated with glacier movements. Loess formations, however, represent layers of settling dust and are not well-sorted.

The formation and movements of dune fields are also of great interest to extraterrestrial or planetary geologists. Analysis of **satellite** images of Mars, for example, allows calculation of the strength and direction of the Martian winds and provides insight into Martian atmospheric dynamics. Dunes fields are a significant Martian landform and many have high rates of migration.

See also Beach and shoreline dynamics; Bed or traction load; Bedforms (ripples and dunes); Desert and desertification; Eolian processes; Glacial landforms; Landscape evolution

DUST STORMS

Dust storms are windstorms that severely blow dust **clouds** across a large **area** in arid or semi-arid regions. Dust storms are different from dust devils, which are small atmospheric dust-filled vortices created by differences in surface heating during fair, hot **weather**. Dust storms can cause poor air quality, decrease visibility, can be hazardous to human and animal health, can interfere with telecommunications, erode away the topsoil, block sunlight, and even can greatly influence not only local, but regional and global weather patterns by accumulating and transporting dust in the atmosphere. For example, after a dust storm in the Sahara, dust can move up to high altitudes, and can be carried hundreds or even thousands of miles away by air streams, causing an illness destroying Caribbean **coral reefs**, resulting in asthma outbreaks in the United States, or providing good nutrients to the Amazonian rain **forests**. Another example is the dust storm in 2001 that began in Mongolia and gathered industrial pollution from China, then caused a haze in a quarter of the United States mainland.

Poor planting methods, extended periods of drought, and high winds were all factors contributing to the generation of dust storms during the Dust Bowl in the 1930s. *AP/Wide World. Reproduced by permission.*

Although dust storms occur naturally, some anthropogenic activity such as removal of vegetation or overgrazing can increase the amount of sediment available for dust storm events. An example of a prolonged impact of dust storms is the historical event called Dust Bowl in the 1930s, which was a disaster both with ecological and societal consequences. The Dust Bowl took place in the southern Great Plains of the United States, including parts of Kansas, Oklahoma, Texas, New Mexico, and Colorado, and was caused by the combination of poor agricultural practices and years of sustained **drought**. Extreme weather and artificially eroded soils resulted in terrible dust storms alternating with drought, heat, **blizzards** and **floods**. The land dried up because the original grasslands holding the **soil** in place were either plowed, then planted with wheat for many years, or because of overgrazing. Consequently, great clouds of dust and **sand** carried by the **wind** covered the area, sometimes even reaching as far as the Atlantic coast. In many places 8–10 cm (3–4 in) of topsoil was blown away. In 1935, programs for soil conservation and for rehabilitation of the Dust Bowl started, including seeding large areas in grass, crop **rotation**, contour plowing, terracing, and strip planting. Accordingly, subsequent droughts in the region had a much less impact, because the available dust for dust storms was greatly reduced by improved agricultural practices.

See also Desert and desertification; Erosion

E

EARLE, SYLVIA A. (1935-)

American oceanographer

Sylvia A. Earle is a former chief scientist of the National Oceanic and Atmospheric Administration (NOAA) and a leading American oceanographer. She was among the first underwater explorers to make use of modern self-contained underwater breathing apparatus (SCUBA) gear, and identified many new species of marine life. With her former husband, Graham Hawkes, Earle designed and built a submersible craft that could dive to unprecedented depths of 3,000 feet.

Sylvia Alice (Reade) Earle was born in Gibbstown, New Jersey, the daughter of Lewis Reade and Alice Freas (Richie) Earle. Both parents had an affinity for the outdoors and encouraged her love of nature after the family moved to the west coast of Florida. As Earle explained to *Scientific American*, "I wasn't shown frogs with the attitude 'yuk,' but rather my mother would show my brothers and me how beautiful they are and how fascinating it was to look at their gorgeous golden eyes." However, Earle pointed out, while her parents totally supported her interest in biology, they also wanted her to get her teaching credentials and learn to type, "just in case."

She enrolled at Florida State University and received her Bachelor of Science degree in the spring of 1955. That fall she entered the graduate program at Duke University and obtained her master's degree in botany the following year. The **Gulf of Mexico** became a natural laboratory for Earle's work. Her master's dissertation, a detailed study of algae in the Gulf, is a project she still follows. She has collected more than 20,000 samples. "When I began making collections in the Gulf, it was a very different body of **water** than it is now—the habitats have changed. So I have a very interesting baseline," she noted in *Scientific American*.

In 1966, Earle received her Ph.D. from Duke University and immediately accepted a position as resident director of the Cape Haze Marine Laboratories in Sarasota, Florida. The following year, she moved to Massachusetts to accept dual roles as research scholar at the Radcliffe Institute and research fellow at the Farlow Herbarium, Harvard University, where she was named researcher in 1975. Earle moved to San Francisco in 1976 to become a research biologist at and curator of the California Academy of Sciences. That same year, she also was named a fellow in botany at the Natural History Museum, University of California, Berkeley.

Although her academic career could have kept her totally involved, her first love was the sea and the life within it. In 1970, Earle and four other oceanographers lived in an underwater chamber for 14 days as part of the government-funded Tektite II Project, designed to study undersea habitats. Fortunately, technology played a major role in Earle's future. A self-contained underwater breathing apparatus had been developed in part by Jacques Cousteau as early as 1943, and refined during the time Earle was involved in her scholarly research. SCUBA equipment was not only a boon to recreational divers, but it also dramatically changed the study of marine biology. Earle was one of the first researchers to don a mask and **oxygen** tank and observe the various forms of plant and animal habitats beneath the sea, identifying many new species of each. She called her discovery of undersea **dunes** off the Bahama Islands "a simple Lewis and Clark kind of observation." But, she said in *Scientific American*, "the presence of dunes was a significant insight into the formation of the area."

Though Earle set the unbelievable record of freely diving to a depth of 1,250 feet, there were serious depth limitations to SCUBA diving. To study deep-sea marine life would require the assistance of a submersible craft that could dive far deeper. Earle and her former husband, British-born engineer Graham Hawkes, founded Deep Ocean Technology, Inc., and Deep Ocean Engineering, Inc., in 1981, to design and build submersibles. Using a paper napkin, Earle and Hawkes rough-sketched the design for a submersible they called *Deep Rover*, which would serve as a viable tool for biologists. "In those days we were dreaming of going to thirty-five thousand feet," she told *Discover* magazine. "The idea has always been that scientists couldn't be trusted to drive a submersible by themselves because they'd get so involved in their work they'd run into things." *Deep Rover* was built and continues to operate as a mid-water machine in ocean depths ranging 3,000 feet.

In 1990, Earle was named the first woman to serve as chief scientist at the National Oceanic and Atmospheric Administration (NOAA), the agency that conducts underwater research, manages fisheries, and monitors marine spills. She left the position after eighteen months because she felt that she could accomplish more working independently of the government.

Earle, who has logged more than 6,000 hours under water, is the first to decry America's lack of research money being spent on deep-sea studies, noting that of the world's five deep-sea manned submersibles (those capable of diving to 20,000 feet or more), the United States has only one, the *Sea Cliff*. "That's like having one Jeep for all of North America," she said in *Scientific American*. In 1993, Earle worked with a team of Japanese scientists to develop the equipment to send first a remote, then a manned submersible to 36,000 feet. "They have money from their government," she told *Scientific American*. "They do what we do not: they really make a substantial commitment to ocean technology and science." Earle also plans to lead the $10 million deep ocean engineering project, Ocean Everest, that would take her to a similar depth.

In addition to publishing numerous scientific papers on marine life, Earle is a devout advocate of public education regarding the importance of the **oceans** as an essential environmental habitat. She is currently the president and chief executive officer of Deep Ocean Technology and Deep Ocean Engineering in Oakland, California, as well as the co-author of *Exploring the Deep Frontier: The Adventure of Man in the Sea*.

See also Deep sea exploration; Ocean circulation and currents

EARTH, INTERIOR STRUCTURE

It is 3,950 miles (6,370 km) from the earth's surface to its center. The **rock** units and layers near the surface are understood from direct observation, core samples, and drilling projects. However, the depth of drill holes, and therefore, the direct observation of Earth materials at depth, is severely limited. Even the deepest drill holes (7.5 mi, 12 km) penetrate less than 0.2% of the distance to the earth's center. Thus, far more is known about the layers near the earth's surface, and scientists can only investigate the conditions within the earth's interior (density, **temperature**, composition, solid versus liquid phase, etc.) through more indirect means.

Geologists collect information about Earth's remote interior from several different sources. Some rocks found at the earth's surface, known as kimberlite and ophiolite, originate deep in the **crust** and mantle. Some meteorites are also believed to be representative of the rocks of the earth's mantle and core. These rocks provide geologists with some idea of the composition of the interior.

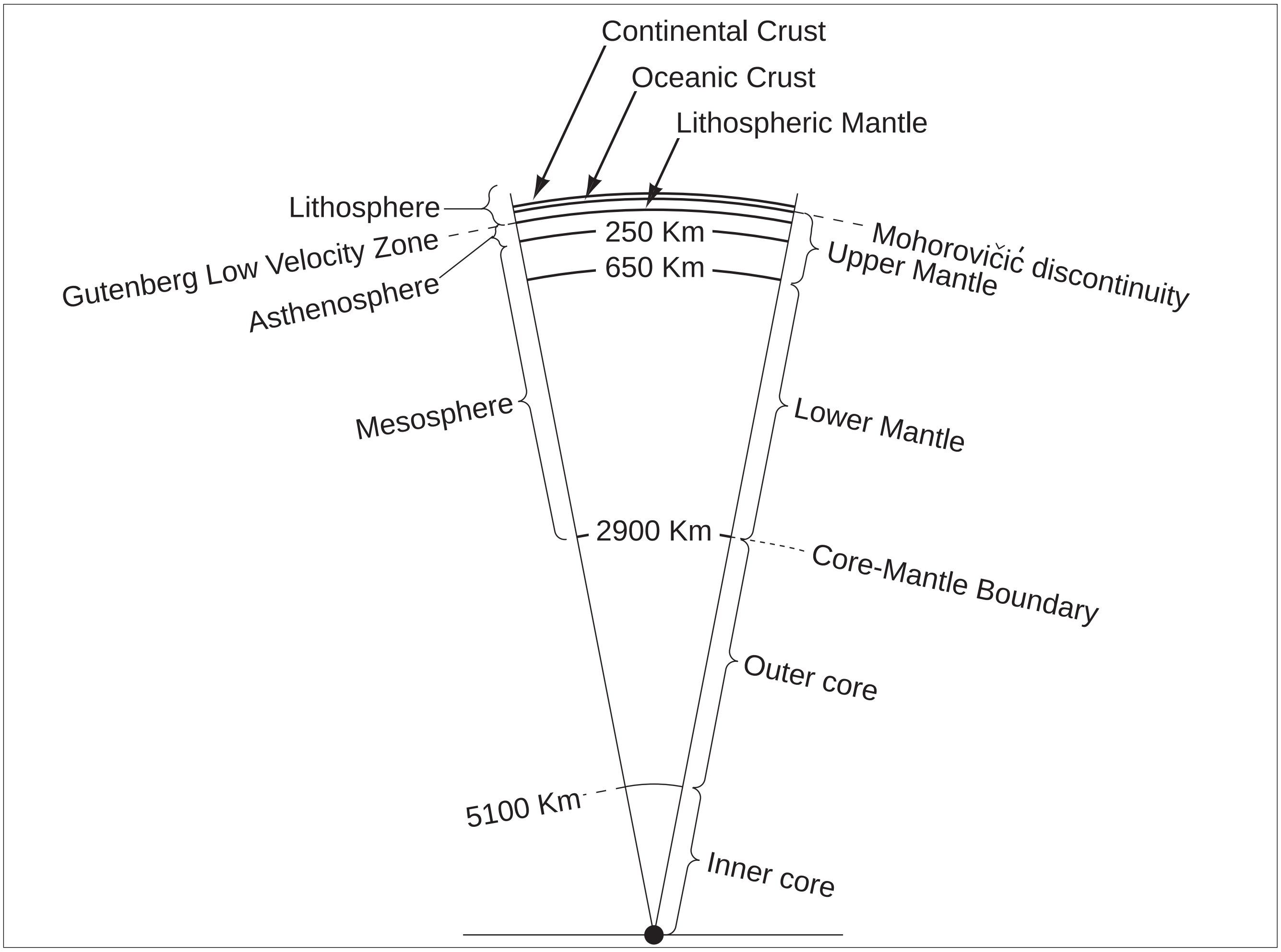
Another source of information, while more indirect, is perhaps more important. That source is **earthquake**, or seismic waves. When an earthquake occurs anywhere on Earth, seismic waves travel outward from the earthquake's center. The speed, motion, and direction of seismic waves changes dramatically at different levels within Earth, known as seismic transition zones. Therefore, scientists can make various assumptions about the earth's character above and below these transition zones through careful analysis of seismic data. This information reveals that Earth is composed of three basic sections, the crust (the thin outer layer), the mantle, and the core.

The outermost layer of Earth is the crust, or the thin "shell" of rock that covers the globe. There are two types of crust: the continental crust, which consists mostly of light-colored rock of granitic composition that underlies the earth's continents; and the oceanic crust, which is a dark-colored rock of basaltic composition that underlies the **oceans**. One of the most important differences between continental and oceanic crust is their difference in density. The lighter-colored continental crust is also lighter in weight, with an average density of 2.6 g/cm^3 (grams per cubic centimeter), compared to the darker and heavier basaltic oceanic crust, which has an average density of 3.0 g/cm^3. It is this difference in density that causes the continents to have an average elevation of about 2,000 ft (600 m) above sea level, while the average elevation (depth) of the ocean bottom is 10,000 ft (3,000 m) below sea level. The heavier oceanic crust sits lower on the earth's surface, creating the topographic depressions for the ocean basins, while the lighter continental crust rests higher on the earth's surface, causing the elevated and exposed continental land masses.

Another difference between the oceanic crust and continental crust is the difference in thickness. The heavier oceanic crust forms a relatively thin layer of 3–6 mi (5–10 km), while the continental crust is lighter, and the underlying material can support a thicker layer. The continental crust averages about 20 mi (35 km) thick, but can reach up to 40 mi (70 km) in certain sections, particularly those found under newly elevated and exposed mountain ranges such as the Himalayas.

The base of the crust (both the oceanic and continental varieties) is determined by a distinct seismic transition zone called the Mohorovičic discontinuity. The Mohorovičic discontinuity, commonly referred to as "the Moho" or the "M-discontinuity," is the transition or boundary zone between the bottom of the earth's crust and the underlying unit, which is the uppermost section of the mantle called the lithospheric mantle. Like the crust, the lithospheric mantle is solid, but it is considerably more dense. Because the thickness of the earth's crust varies, the depth to the Moho also varies from 3–6 mi (5–10 km) under the oceans to 20–40 mi (35-70 km) under the continents.

This transition between the crust and the mantle was first discovered by the Croatian seismologist Andrija Mohorovičic in 1908. On October 8, 1908, Andrija Mohorovičic observed seismic waves that emitted from an earthquake in Croatia. He noticed that both the compressional, or primary (P), waves and the shear, or secondary (S), waves, at one point in their journey, picked up speed as they traveled



Interior structure of Earth.

farther from the earthquake. This suggested that the waves had been deflected, as if they had encountered something that had affected their energy. He noted that this increase in speed seemed to occur at a depth of about 30 mi (50 km). Since seismic waves travel faster through denser material, he reasoned that there was an abrupt transition from the rocky material in the earth's crust, to denser rocks below. In honor of Andrija Mohorovičic's discovery, this transition zone marking the base of the earth's crust was named after him.

The Moho is a relatively narrow transition zone estimated to be somewhere between 0.1–1.9 mi (0.2–3 km) thick. Currently, the Moho is defined by the level within Earth where P wave velocity increases abruptly from an average speed of about 4.3 mi/second (6.9 km/second) to about 5.0 mi/second (8.1 km/second).

Underlying the crust is the mantle. The uppermost section of the mantle, which is a rigid layer, is called the lithospheric mantle. This section extends to an average depth of about 40 mi (70 km), although it fluctuates between 30–60 mi (50–100 km). The density of this layer is greater than that of the crust, and averages 3.3 g/cm^3. But like the crust, this section is solid and brittle, and relatively cool compared to the material below. This rigid uppermost section of the mantle (the lithospheric mantle), combined with the overlying solid crust, is called the **lithosphere**, which is derived from the Greek word *lithos*, meaning rock. At the base of the lithosphere, a depth of about 40 mi (70 km), there is another distinct seismic transition called the Gutenberg low velocity zone. At this level, the velocity of S waves decreases dramatically, and all seismic waves appear to be absorbed more strongly than elsewhere within the earth. Scientists interpret this to mean that the layer below the lithosphere is a softer zone of partially melted material (with between 1–10% molten material). This "soft" zone is called the *asthenosphere*, from the Greek word *asthenes* meaning weak. This transition zone between the lithosphere and the **asthenosphere** is named after Beno Gutenberg, a mid-twentieth century geologist who made several important contributions to the study and understanding of the earth's interior. It is at this level that some important Earth dynamics occur, affecting those at the surface. At the Gutenberg low velocity zone, the lithosphere is carried "piggyback" on top of the weaker, less rigid asthenosphere, which seems to be in continual motion. This motion creates stress in the rigid rock layers above it, and the slabs or plates of the lithosphere are forced to jostle against each other, much like **ice** cubes floating in a bowl of swirling **water**. This motion of the **lithospheric plates** is known as **plate tectonics**, and it is responsible for many of the earth's activities that we experience at the surface today, including earthquakes, certain types of volcanic activity, and continental drift.

The asthenosphere extends to a depth of about 155 mi (250 km). Below that depth, seismic wave velocity increases, suggesting an underlying denser, but solid phase.

The rest of the mantle, from the base of the asthenosphere at 155 mi (250) km to the core at 1,800 mi (2,900 km), is called the **mesosphere** (or middle sphere). There are mineralogical and compositional changes suggested by sharp velocity increases within the mesosphere. Notably, there is a thin zone at about the 250 mi (400 km) depth attributed to a possible mineralogical change (presumably from an abundance of the mineral **olivine** to the mineral spinel), and there is another sharp velocity increase at about the 400 mi (650 km) level, attributed to a possible increase in the ratio of **iron** to magnesium in mantle rocks. Except for these variations, down to the 560 mi (900 km) level the mesosphere seems to contain predominantly solid material that displays a relatively consistent pattern of gradually increasing density and seismic wave velocity with increasing depth and pressure. Below the 560 mi (900 km) depth, the P and S wave velocities continue to increase, but the rate of increase declines with depth.

At a depth of 1,800 mi (2,900 km) there is another abrupt change in the seismic wave patterns, known as the Gutenberg discontinuity, or more often referred to as the core-mantle boundary (CMB). At this level, P waves decrease while S waves disappear completely. Since S waves cannot be transmitted through liquids, it is believed that the CMB denotes a phase change from the solid mantle above, to a liquid outer core below. This phase change is believed to be accompanied by an abrupt temperature increase of 1,300° F (704° C). This hot, liquid outer core material is denser than the cooler, solid mantle, probably due to a greater percentage of iron. It is believed that the outer core consists of a liquid of 80–92% iron, alloyed with a lighter element. The composition of the remaining 8–20% is not well understood, but it must be a compressible element that can mix with liquid iron at these immense pressures. Various candidates proposed for this element include **silicon**, sulfur, or **oxygen**.

The actual boundary between the mantle and the outer core is a narrow, uneven zone that contains undulations that may be 3–6 mi (5–8 km) high. These undulations are affected by heat-driven convection activity within the overlying mantle, which may be the driving force for plate tectonics. The interaction between the solid mantle and the liquid outer core is very important to Earth dynamics for another reason. It is the eddies and currents in the core's iron-rich fluids that are ultimately responsible for the earth's **magnetic field**.

Although the core-mantle boundary is currently situated at a depth of about 1,800 mi (2,900 km), this depth has not been constant through **geologic time**. As the heat of the earth's interior is constantly but slowly dissipated, the molten core within the earth gradually solidifies and shrinks, causing the core-mantle boundary to slowly move deeper and deeper within the earth's core.

There is one final, even deeper transition evident from seismic wave data. Within Earth's core, at the 3,150 mi (5,100 km) level, P waves speed up and are reflected from yet another seismic transition zone. This indicates that the material in the inner core below 3,150 mi (5,100 km) is solid. The phase change from liquid to solid is probably due to the immense pressures present at this depth.

In addition to this phase change in the inner core from liquid to solid, seismic wave velocities, as well as the earth's total weight, suggest that the inner core has a different composition than the outer core. This could be accounted for by a relatively pure iron-nickel composition for the inner core. Although no direct terrestrial evidence for a solid iron-nickel inner core exists, comparative evidence from meteorites supports this theory. Numerous meteorites, fragments presumably from the interior of shattered extraterrestrial bodies within our **solar system**, often contain relatively pure iron or iron-nickel compositions. It is likely that the composition of the core of our own planet is very similar to the composition of these extraterrestrial travelers.

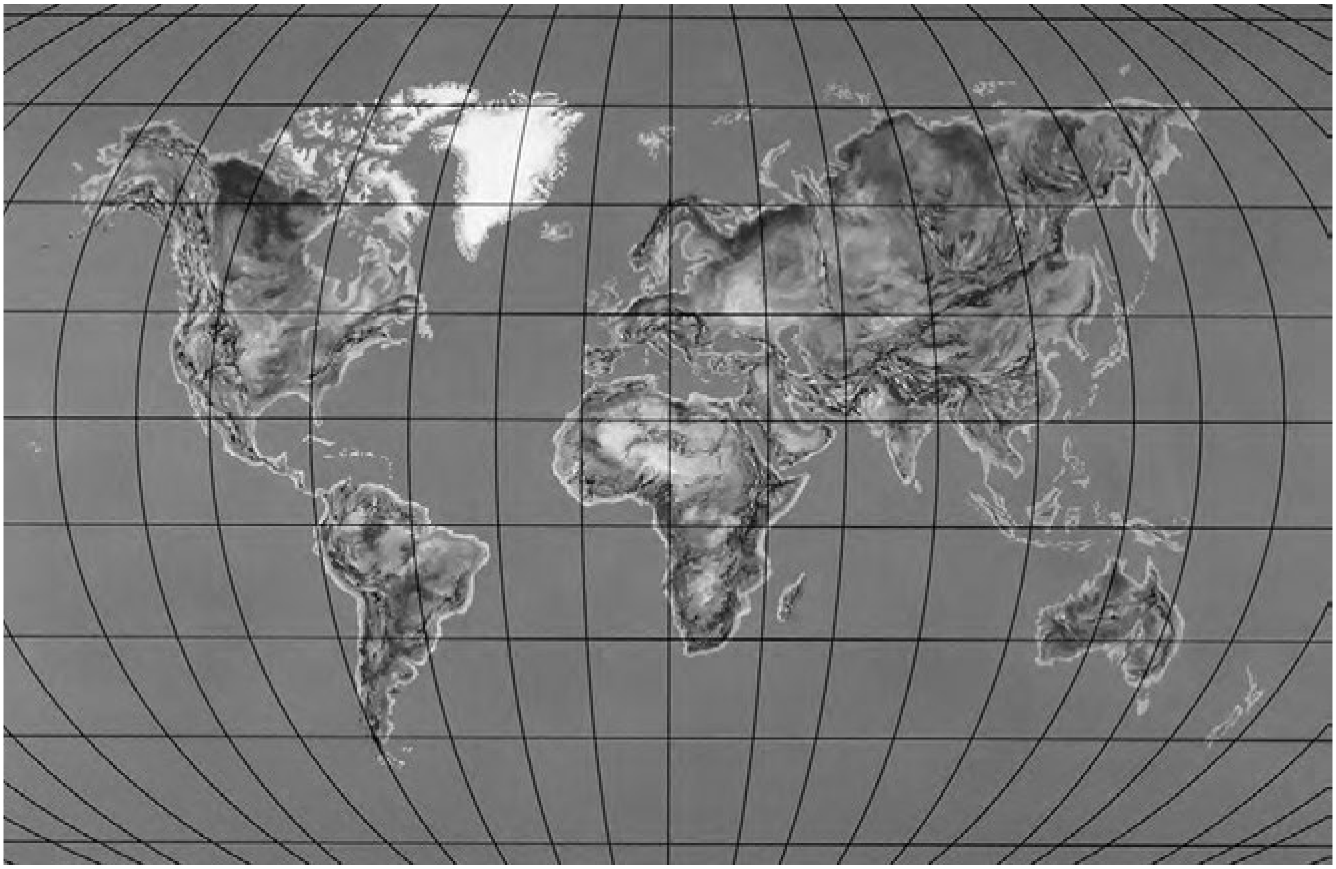
See also Earth (planet); Earth science; Seismograph; Seismology; Volcanic eruptions; Volcanic vent

EARTH OBSERVING SYSTEMS (EOS) • *see* TERRA SATELLITE AND EARTH OBSERVING SYSTEMS (EOS)

EARTH, PLANET

Earth is the third of nine planets in our **solar system**. Its surface is mostly **water** (about 70%), and it has a moderately dense nitrogen and **oxygen** atmosphere that supports life. Rich in **iron** and nickel, Earth is a dense, molten oblate sphere with a solid core and a thin outer **crust**. Earth rotates about its **polar axis** as it revolves around the **Sun**. Earth has one natural **satellite**, the **Moon**. A complete **revolution** of Earth around the Sun takes about one year, while a **rotation** on its axis takes one day. The surface of Earth is constantly changing, as tectonic plates slowly move about on the turbulent foundation of partially molten **rock** beneath them. Collisions between landmasses build mountains; **erosion** wears them down. Slow changes in the **climate** cause equally slow changes in vegetation and animals.

Earth orbits the Sun at a distance of about 93,000,000 mi (150,000,000 km), taking 365.25 days to complete one revolution. Earth is small by planetary standards, only one-tenth the size of Jupiter. The equatorial radius of the earth is about 6,378 km. The polar radius of the earth is about 6,357 km. The difference is due to centrifugal flattening. Earth's mass is estimated at approximately 6.0×10^{24} kg. The difference is due to centrifugal flattening. Unlike the outer planets, which are composed mainly of light gases, Earth is made of heavy elements such as iron and nickel, and is, therefore, much more



Topographic map of planet Earth. © *Tecmap Corporation, Eric Curry/Corbis. Reproduced by permission.*

dense. These characteristics—small and dense—are typical of the inner four terrestrial planets.

About 4.5 to 5.1 billion years ago, the solar system formed from a contracting cloud of interstellar gas. The cloud underwent compression and heating as it shrank, until its central part blazed forth as the mature, stable star. As the Sun formed, the surrounding gas cloud flattened into a disk. In this disk, the first solid particles formed and then grew as they accreted additional matter from the surrounding gas. Soon sub-planetary bodies, called planetesimals, built up, and then they collided and merged, forming the planets. The high temperatures in the inner solar system ensured that only the heavy elements, those that form rock and metal, could survive in solid form.

Thus were formed the small, dense terrestrial planets. Hot at first due to the collisions that formed it, Earth began to cool. Its components began to differentiate, or separate themselves according to their density. To its core went the heavy abundant elements, iron and nickel. Outside the core were numerous elements compressed into a dense but pliable substance called the mantle. Finally, a thin shell of cool, oxygen- and silicon-rich rock formed at Earth's surface: the crust, or **lithosphere**. Formation of the crust from the initial molten mass took half a billion years.

Earth's atmosphere formed as a result of outgassing of **carbon dioxide** from its interior, and accretion of gases from **space**, including elements brought to Earth by **comets**. The lightest elements, such as helium and most of the hydrogen, escaped to space, leaving behind an early atmosphere consisting of hydrogen compounds such as methane and ammonia as well as water vapor and nitrogen- and sulfur-bearing compounds released by volcanoes. **Carbon** dioxide was also plentiful, but was soon dissolved in ocean waters and deposited in carbonate rocks. As the gases cooled, they condensed, and rains inundated the planet. The lithosphere was uneven, containing highlands made of buoyant rock such as **granite**, and basins of heavy, denser **basalt**. Into these giant basins the rains flowed, forming the **oceans**. Eventually life forms appeared, and over the course of a billion years, plants enriched the atmosphere with oxygen, finally producing the nitrogen-oxygen atmosphere we have today.

Earth's crust is in a constant, though slow, state of change. Landmasses move, collide, and break apart according to a process called **plate tectonics**. The lithosphere (the outer crust and a portion of the upper mantle) is not one huge shell of rock; it is composed of several large pieces called plates. These pieces are constantly in motion, because Earth's interior is dynamic, with its core still molten and with large-scale convective currents in the upper mantle. The thermal forces move the plates a few centimeters a year, but this is enough to have profound consequences over the long expanse of **geologic time**.

For instance, the center of the North American continent is the wide open expanse of the Great Plains and the Canadian Prairies. On the eastern edge, the rolling **folds** of the Appalachian Mountains grace western North Carolina, Virginia, and Pennsylvania. In the west, the jagged, crumpled Rockies thrust skyward, tall, stark, and snow-capped.

These two great ranges represent one of the two basic land-altering processes: mountain building. Two hundred million years ago, **North America** was moving east, driven by plate tectonics. In a shattering, slow-motion collision, it rammed into what is now **Europe** and North **Africa**. The land crumpled, and the ancient Appalachians rose. At that time, they were the mightiest mountains on Earth. A hundred million years later, North America was driven back west. Now the western edge of the continent rumbled along over the Pacific plate, and about 80 million years ago, a massive spate of mountain building formed the Rockies.

During the time since the Appalachians rose, the other land-altering process, erosion, has reshaped the landscape. Battered by **wind** and water, their once sheer mountain flanks have been worn into the low, rolling hills of today.

Mountain building can be seen today in the Himalayas, which are still rising as India moves northward into **Asia**, crumpling parts of Nepal and Tibet. Erosion rules in Arizona's Grand **Canyon**, which gradually is deepening and widening as the Colorado River slices now into ancient granite two billion years old.

This unending cycle of mountain building (caused by movement of the crustal plates) and erosion (by wind and water) has formed every part of Earth's surface today. Where there are mountains, as in the long ranks of the Andes or the Urals, there is subterranean conflict. Where a crustal plate rides over another one, burying and **melting** it in the hot regions below the lithosphere, volcanoes rise, dramatically illustrated by Mt. St. Helens in Washington and the other volcanoes that line the Pacific rim. Where lands lie wide and arid, they are sculpted into long, scalloped cliffs, as one sees in the deserts of New Mexico, Arizona, and Utah.

Earth is mostly covered with water. The Pacific Ocean covers nearly half of Earth; from the proper vantage point in space above the middle of the Pacific Ocean, one would see nothing but water, dotted here and there with tiny islands, with only **Australia** and the coasts of Asia and the Americas rimming the edge of the globe.

The lithosphere rides on a pliable layer of rock in the upper mantle called the **asthenosphere**. Parts of the lithosphere are made of relatively light rocks (continental crust), while others (oceanic crust) are made of heavier, denser rocks. Just as corks float mostly above water while **ice** cubes float nearly submerged, the less dense parts of the lithosphere ride higher on the asthenosphere than the more dense ones. Earth therefore has huge basins, and early in the planet's history, these basins filled with water condensing and raining out of the primordial atmosphere. Additional water was brought to Earth by the impacts of comets, whose nuclei are made of water ice.

The atmosphere has large circulation patterns, and so do the oceans. Massive streams of warm and cold water flow through them. One of the most familiar is the **Gulf Stream**, which brings warm water up the eastern coast of the United States.

Circulation patterns in the oceans and in the atmosphere are driven by **temperature** differences between adjacent areas and by the rotation of Earth, which helps create circular, or rotary, flows. Oceans play a critical role in the overall energy balance and **weather** patterns. Storms are ultimately generated by moisture in the atmosphere, and **evaporation** from the oceans is the prime source of such moisture. Oceans respond less dramatically to changes in energy input than land does, so the temperature over a given patch of ocean is far more stable than one on land.

Earth's atmosphere is the gaseous region above its outer crust, composed of nitrogen (78% by number), oxygen (21%), and other gases (1%). It is only about 50 mi (80 km) from the ground to space: on a typical, 12-in (30 cm) globe the atmosphere would be less than 2 mm thick. The atmosphere has several layers. The most dense and significant of these is the **troposphere**; all weather occurs in this layer, and commercial jets cruise near its upper boundary, 6 mi (10 km) above Earth's surface. The **stratosphere** lies between 6 and 31 mi (10 and 50 km) above, and it is here that the ozone layer lies. In the **mesosphere** and the **thermosphere** one finds auroras occurring after eruptions on the Sun; radio communications "bounce" off the **ionosphere** back to Earth.

The atmosphere is an insulator of almost miraculous stability. Only 50 mi (80 km) away is the cold of outer space, but the surface remains temperate. Heat is stored by the land and the atmosphere during the day, but the resulting heat radiation (infrared) from the surface is prevented from radiating away by gases in the atmosphere that trap infrared radiation. This is the well-known **greenhouse effect**, and it plays an important role in the atmospheric energy budget. According to some models, a global temperature decrease of two degrees could trigger the next advance of an ice age, while an increase of three degrees could melt the **polar ice** caps, submerging nearly every coastal city in the world.

Despite this overall stability, the troposphere is nevertheless a turbulent place. It is in a state of constant circulation, driven by Earth's rotation as well as the constant heating and cooling that occurs during each 24-hour period.

The largest circulation patterns in the troposphere are the Hadley cells. There are three of them in each hemisphere, with the middle, or Ferrel cell, lying over the latitudes spanned by the continental United States. Northward-flowing surface air in the Ferrel cell is deflected toward the east by the Coriolis force, with the result that winds—and weather systems—move from west to east in the middle latitudes of the northern hemisphere.

Near the top of the troposphere are the jet streams, fast-flowing currents of air that circle Earth in sinuous paths.

Circulation on a smaller but violent scale appears in the cyclones and anticyclones, commonly called low and high pressure cells. Lows typically bring unsettled or stormy weather, while highs mean sunny skies. Weather in most areas follows a basic pattern of alternating calm weather and storms, as the endless progression of highs and lows, generated by Earth's rotation and temperature variation, passes by. This is a great simplification, however, and weather in any given place may be affected, or even dominated, by local features. The climate in Los Angeles, California is entirely different from that in Las Vegas, Nevada though the two cities are not very far apart. Here, local features—specifically, the mountains between them—are as important as the larger circulation patterns.

Earth has a **magnetic field** that extends tens of thousands of kilometers into space and shields Earth from most of the solar wind, a stream of particles emitted by the Sun. Sudden enhancements in the solar wind, such as a surge of particles ejected by an eruption in the Sun's atmosphere, may disrupt the magnetic field, temporarily interrupting long-range radio communications and creating brilliant displays of auroras near the poles, where the magnetic field lines bring the charged particles close to the earth's surface.

Farther out, at a mean distance of about 248,400 mi (400,000 km), is Earth's only natural satellite, the Moon. Some astronomers assert that the Earth and the Moon should properly be considered a "double planet," since the Moon is larger relative to our planet than the satellites of most other planets.

The presence of life on Earth is, as far as we know, unique. Men have walked on the Moon, and there is no life on our barren, airless satellite. Unmanned spacecraft have landed on Venus and Mars and have flown close to every other planet in the solar system except Pluto. The most promising possibility, Mars, yielded nothing to the automated experiments performed by the Viking and Mars Surveyor spacecraft that searched for signs of extraterrestrial life.

See also Atmospheric composition and structure; Biogeochemical cycles; Continental drift theory; Cosmology; Earth science; Earth, interior structure; Evolution, evidence of; Evolutionary mechanisms; Gaia hypothesis; Geochemistry; Geologic time; Global warming; Greenhouse gases and greenhouse effect; History of exploration I (Ancient and classical); History of exploration II (Age of exploration); History of exploration III (Modern era); Hydrologic cycle; Landforms; Landscape evolution; Latitude and longitude; Marine transgression and marine regression; Miller-Urey experiment; Oceanography; Origin of life; Orogeny; Revolution and rotation; Space and planetary geology; Supercontinents; Terra satellite and Earth Observing Systems (EOS); Uniformitarianism; Weather and climate

EARTH SCIENCE

Befitting a dynamic Earth, the study of Earth science embraces a multitude of subdisciplines. To understand the complexities of Earth, one must see the patterns of complex interaction through the eyes of the physicist, chemist, geologist, meterologist, and explorer. Just as no single agency has the responsibility to collect geophysical data—in fact there are hundreds worldwide—no single discipline provides the insight to understand or explain all of Earth's complexities.

Moreover, just a cooperation and collaboration are essential for gathering data, an interdisciplinary approach to Earth science is essential to proper evaluation of that data.

At the heart of Earth science is the study of **geology**. Literally meaning "to study the Earth," traditional geological studies of rocks, **minerals**, and local formations have within the last century, especially in the light of the development of plate tectonic theory, broadened to include studies of geophysics and **geochemistry** that offer sweeping and powerful explanations of how continents move, to explanations of the geochemical mechanisms by which **magma** cools and hardens into a multitude of **igneous rocks**.

Earth's formation and the **evolution** of life upon its fragile outer **crust** was dependent upon the conditions established during the formation of the **solar system**. The **Sun** provides the energy for life and drives the turbulent atmosphere. A study of Earth science must, therefore, not ignore a treatment of Earth as an astronomical body in **space**.

At the opposite extreme, deep within Earth's interior, radioactive decay adds to the heat left over from the **condensation** of Earth from cosmic dust. This heat drives the forces of **plate tectonics** and results in the tremendous variety of features that distinguish Earth. To understand Earth's interior structure and dynamics, seismologists probe the interior structure with seismic shock waves.

It does not require the spectacular hurricane, **tornado**, **landslide**, or volcanic eruption to prove that Earth's atmosphere and **seas** are dynamic entities. Forces that change and shape the Earth appear on a daily basis in the form of **wind** and **tides**. What Earth scientists, including meteorologists and oceanographers seek to explain—and ultimately to quantify—are the physical mechanisms of change and the consequences of those changes. Only by understanding the mechanisms of change can predictions of **weather** or climatic change hope to achieve greater accuracy.

The fusion of disciplines under the umbrella of Earth science allows a multidisciplinary approach to solving complex problems or multi-faceted issues of resource management. In a addition to hydrogeologists and cartographers, a study of ground **water** resources could, for example, draw upon a wide diversity of Earth science specialists.

Although modern Earth Science is a vibrant field with research in a number of important and topical areas (e.g., identification of energy resources, **waste disposal** sites, etc), the span of geological process and the enormous expanse of **geologic time** make critical the study of ancient processes (e.g., paleogeological studies). Only by understanding how processes have shaped Earth in the past—and through a detailed examination of the geological record—can modern science construct meaningful predictions of the potential changes and challenges that lie ahead.

See also Astronomy; Chemistry; Earth (planet); Field methods in geology; Geochemistry; Historical geology; History of exploration I (Ancient and classical); History of exploration II (Age of exploration); History of exploration III (Modern era); History of geoscience: Women in the history of geoscience; History of manned space exploration; Oceanography; Physics;

Scientific data management in Earth Sciences; Space and planetary geology

EARTHQUAKE

An earthquake is a geological event inside the earth that generates strong vibrations. When the vibrations reach the surface, the earth shakes, often causing damage to natural and manmade objects, and sometimes killing and injuring people and destroying their property. Earthquakes can occur for a variety of reasons; however, the most common source of earthquakes is movement along a fault.

Some earthquakes occur when tectonic plates, large sections of Earth's **crust** and upper mantle, move past each other. Earthquakes along the San Andreas and Hayward faults in California occur because of this. Earthquakes also occur if one plate overruns another, as on the western coast of **South America**, the northwest coast of **North America**, and in Japan. If plates collide but neither is overrun, as they do crossing **Europe** and **Asia** from Spain to Vietnam, earthquakes result as the rocks at the abutting plates compress into high mountain ranges. In all three of these settings, earthquakes result from movement along faults.

A fault block may also move due to **gravity**, sinking between other fault blocks that surround and support it. Sinking fault blocks and the mountains that surround them form a distinctive **topography** of basins and mountain ranges. This type of fault block configuration is typified by the North American Basin and Range topographic province. In such places, elevation losses by the valleys as they sink between the mountains are accompanied by tremors or earthquakes. Another kind of mountain range rises because of an active thrust fault. Tectonic compression (tectonic, meaning having to do with the forces that deform the rocks of planets) shoves the range up the active thrust fault, which acts like a natural ramp.

Molten **rock** called **magma** moves beneath but relatively close to the earth's surface in volcanically active regions. Earthquakes sometimes accompany **volcanic eruptions** as huge masses of magma move underground.

Nuclear bombs exploding underground cause small local earthquakes, which can be felt by people standing within a few miles of the test site. The earthquakes caused by nuclear bombs are tiny compared to natural earthquakes; but they have a distinctive "sound," and their location can be pinpointed. This is how nuclear weapons testing in one country can be monitored by other countries around the world.

Earth is covered by a crust of solid rock, which is broken into numerous plates that move around on the surface, bumping, overrunning, and pulling away from each other. One kind of boundary between rocks within a plate, as well as at the edges of the plates, is a fault. Faults are large-scale breaks in Earth's crust, in which the rock on one side of the fault has been moved relative to the rock on the other side of the fault by tectonic forces. Fault blocks are giant pieces of crust that are separated from the rocks around them by faults.

When the forces pushing on fault blocks cannot move one block past the other, potential energy is stored up in the fault zone. This is the same potential energy that resides in a giant boulder when it is poised, motionless, at the top of a steep slope. If something happens to overcome the friction holding the boulder in place, its potential energy will convert into kinetic energy as it thunders down the slope. In the fault zone, the potential energy builds up until the friction that sticks the fault blocks together is overcome. Then, in seconds, all the potential energy built up over the years turns to kinetic energy as the rocks surge past each other.

The vibrations of a fault block on the move can be detected by delicate instruments (seismometers and seismographs) in rocks on the other side of the world. Although this happens on a grand scale, it is remarkably like pushing on a stuck window or sliding door. Friction holds the window or door tight in its tracks. After enough force is applied to overcome the friction, the window or door jerks open.

Some fault blocks are stable and no longer experience the forces that moved them in the first place. The fault blocks that face each other across an active fault, however, are still influenced by tectonic forces in the ever-moving crust. They grind past each other along the fault as they move in different directions.

Fault blocks can move in a variety of ways, and these movements define the different types of faults. In a vertical fault, one block moves upward relative to the other. At the surface of the earth, a vertical fault forms a cliff, known as a fault scarp. The sheer eastern face of the Sierra Nevada mountain range is a fault scarp. In most vertical faults, the fault scarp is not truly vertical, and one of the fault blocks "hangs" over the other. This upper block is called the hanging wall and the lower block, the foot wall.

In horizontal faults, the blocks slide past one another without either block being lifted. In this case, the objects on the two sides of the fault simply slide past one another; for example, a road that straddles the fault might be offset by a number of feet. Complex faults display movements with both vertical and horizontal displacements.

Any one of the following fault types can generate an earthquake:

- Normal fault—A vertical fault in which the hanging wall moves down compared to the foot wall.
- Reverse fault—A vertical fault in which the hanging wall moves up in elevation relative to the foot wall.
- Thrust fault—A low-angle (less than 30°) reverse fault, similar to an inclined floor or ramp. The lower fault block is the ramp itself, and the upper fault block is gradually shoved up the ramp. The "ramp" may be shallow, steep, or even curved, but the motion of the upper fault block is always in an upward direction. A thrust fault caused the January 1994 Northridge earthquake near Los Angeles, California.
- Strike-slip (or transform) fault—A fault along which one fault block moves horizontally (sideways), past another fault block, like opposing lanes of traffic. The San Andreas fault in Northern California is one of the best known of this type.

When a falling rock splashes into a motionless pool of **water**, waves move out from the point of impact. These waves appear at the interface of water and air as circular ripples. However, the waves occur below the surface, too, traveling down into the water in a spherical pattern. In rock, as in water, a wave-causing event makes not one wave, but a number of waves, moving out from their source, one after another, like an expanding bubble.

Tectonic forces shift bodies of rock inside the earth, perhaps displacing a mountain range several feet in a few seconds, and they generate tremendous vibrations called seismic waves. The earthquake's focus (also called the hypocenter) is the point (usually deep in the subsurface) where the sudden sliding of one rock mass along a fault releases the stored potential energy of the fault zone. The first shock wave emerges at the surface at a point typically directly above the focus; this surface point is called the epicenter. Seismometers detect seismic waves that reach the surface. Seismographs (devices that record seismic phenomena) record the times of arrival for each group of vibrations on a seismogram (either a paper document or digital data).

Like surfaces in an echoing room that reflect or absorb sound, the boundaries of rock types within the earth change or block the direction of movement of seismic waves. Waves moving out from the earthquake's focus in an ever-expanding sphere become distorted, bent, and reflected. Seismologists (geologists who study seismic phenomena) analyze the distorted patterns made by seismic waves and search through the data for clues about the earth's internal structure.

Different kinds of earthquake-generated waves, moving at their own speeds, arrive at the surface in a particular order. The successive waves that arrive at a single site are called a wave train. Seismologists compare information about wave trains that are recorded as they pass through a number of data-collecting sites after an earthquake. By comparing data from three recording stations, they can pinpoint the map location (epicenter) and depth within the earth's surface (focus or hypocenter) of the earthquake.

These are the most important types of seismic waves:

- P-waves—The fastest waves, these compress or stretch the rock in their path through Earth, moving at about 4 mi (6.4 km) per second.
- S-waves—As they move through Earth, these waves shift the rock in their path up and down and side to side, moving at about 2 mi (3.2 km) per second.
- Rayleigh waves and Love waves—These two types of "surface waves" are named after seismologists. Moving at less than 2 mi (3.2 km) per second, they lag behind P-waves and S-waves but cause the most damage. Rayleigh waves cause the ground surface in their path to ripple with little waves. Love waves move in a zigzag along the ground and can wrench buildings from side to side.

The relative size of earthquakes is measured by the **Richter scale**, which measures the energy an earthquake releases. Each whole number increase in value on the Richter scale indicates a 10-fold increase in the energy released and a thirty-fold increase in ground motion. An earthquake measuring 8 on the Richter scale is ten times more powerful, therefore, than an earthquake with a Richter Magnitude of 7, which is ten times more powerful than an earthquake with a magnitude of 6. Another scale—the Modified Mercalli Scale uses observations of damage (like fallen chimneys) or people's assessments of effects (like mild or severe ground shaking) to describe the intensity of a quake.

Earthquakes are among the most devastating natural disasters because of their unpredictablility, the large area affected, and the irresistible forces they cause. *AP/Wide World. Reproduced by permission.*

Violent shaking changes water bearing **sand** into a liquid-like mass that will not support heavy loads, such as buildings. This phenomenon, called liquefaction, causes much of the destruction associated with an earthquake in liquefaction-prone areas. Downtown Mexico City rests on the old lakebed of Lake Texcoco, which is a large basin filled with liquefiable sand and ground water. In the Mexico City earthquake of 1985, the wet sand beneath tall buildings turned to slurry, as if the buildings stood on the surface of vibrating gelatin in a huge bowl. Most of the 10,000 people who died as a result of that earthquake were in buildings that collapsed as their foundations sank into liquefied sand.

In the sudden rearrangement of fault blocks in the earth's crust that cause an earthquake, the land surface on the dropped-down side of the fault can fall or subside in elevation by several feet. On a populated coastline, this can wipe out a city. Port Royal, on the south shore of Jamaica, subsided several feet in an earthquake in 1692 and suddenly disappeared as the sea rushed into the new depression. Eyewitnesses recounted the seismic destruction of the infamous pirate anchorage, as follows: "...in the space of three minutes, Port-Royall, the fairest town of all the English plantations, exceeding of its riches,...was shaken and shattered to pieces, sunk into and covered, for the greater part by the sea...The earth heaved and swelled like the rolling billows, and in many places the earth crack'd, open'd and shut, with a motion quick and fast...in some of these people were swallowed up, in others they were caught by the middle, and pressed to death...The whole was attended with...the noise of falling mountains at a distance, while the sky...was turned dull and reddish, like a glowing oven." Ships arriving later in the day found a small shattered remnant of the city that was still above the water. Charts of the Jamaican coast soon appeared printed with the words *Port Royall Sunk*.

In the New Madrid (Missouri) earthquake of 1811, a large **area** of land subsided around the bed of the Mississippi River in west Tennessee and Kentucky. The Mississippi was observed to flow backwards as it filled the new depression, to create what is now known as Reelfoot Lake.

Cities depend on networks of so-called "lifeline structures" to distribute water, power, and food and to remove sewage and waste. These networks, whether power lines, water mains, or roads, are easily damaged by earthquakes. Elevated freeways collapse readily, as demonstrated by a section of the San Francisco Bay Bridge in 1989 and the National Highway Number 2 in Kobe, Japan, in 1995. The combination of several networks breaking down at once multiplies the hazard to lives and property. Live power lines fall into water from broken water mains, creating a deadly electric shock hazard. Fires may start at ruptured gas mains or chemical storage tanks. Although emergency services are needed more than ever, many areas may not be accessible to fire trucks and other emergency vehicles. If the water mains are broken, there will be no pressure at the fire hydrants, and the firefighters' hoses are useless. The great fire that swept San Francisco in 1906 could not be stopped by regular firefighting methods. Only dynamiting entire blocks of buildings halted the fire's progress. Both Tokyo and Yokohama burned after the Kwanto earthquake struck Japan in 1923, and 143,000 people died, mostly in the fire.

Popular doomsayers excite uncomprehending fear by saying that earthquakes happen more frequently now than in earlier times. It is true that more people than ever are at risk from earthquakes, but this is because the world's population grows larger every year, and more people are living in earthquake-prone areas.

Today, sensitive seismometers "hear" every noteworthy earth-shaking event, recording it on a seismogram. Seismometers detect earthquake activity around the world, and data from all these instruments are available on the Internet within minutes of the earthquake. News agencies can report the event the same day. People have ready access to information about every earthquake that happens anywhere on Earth. And the earth experiences a lot of earthquakes—the planet never ceases to vibrate with tectonic forces, although the majority of them are not strong enough to be detected except with instruments. Earth has been resounding with earthquakes for more than 4 billion years. Earthquakes are a way of knowing that the planet beneath us is still experiencing normal operating conditions, full of heat and kinetic energy.

Ultrasensitive instruments placed across faults at the surface can measure the slow, almost imperceptible movement of fault blocks, which tell of great potential energy stored at the fault boundary. In some areas, foreshocks (small earthquakes that precede a larger event) may help seismologists predict the larger event. In other areas, where seismologists believe seismic activity should be occurring but is not, this seismic gap may be used instead to predict an inevitable large-scale earthquake.

Other instruments measure additional fault-zone phenomena that seem to be related to earthquakes. The rate at which radon gas issues from rocks near faults has been observed to change before an earthquake. The properties of the rocks themselves (such as their ability to conduct **electricity**) have been observed to change, as the tectonic force exerted on them slowly alters the rocks of the fault zone between earthquakes. Peculiar animal behavior has been reported before many earthquakes, and research into this phenomenon is a legitimate area of scientific inquiry, even though no definite answers have been found.

Techniques of studying earthquakes from space are also being explored. Scientists have found that ground displacements cause waves in the air that travel into the **ionosphere** and disturb electron densities. By using the network of satellites and ground stations that are part of the global positioning system (**GPS**), data about the ionosphere that is already being collected by these satellites can be used to understand the energy releases from earthquakes, which may help in their prediction.

Scientists have presumed that **tides** do not have any influence on or direct relationship to earthquakes. New studies show that tides may sometimes trigger earthquakes on faults where strain has been accumulating; tidal pull during new or full moons has been discounted by studies of over 13,000 earthquakes of which only 95 occurred during these episodes of tidal stress. Attention is also being directed toward the types of rock underlying areas of earthquake activity to see if rock types dampen (lessen the effects) or magnify earthquake motions.

Seismologists must make a hard choice when their data interpretations suggest an earthquake is about to happen. If they fail to warn people of danger they strongly suspect is imminent, many might die needlessly. But, if people are evacuated from a potentially dangerous area and no earthquake occurs, the public will lose confidence in such warnings and might not heed them the next time.

As more is discovered about how and why earthquakes occur, that knowledge can be used to prevent the conditions that allow earthquakes to cause harm. The most effective way to minimize the hazards of earthquakes is to build new buildings or retrofit old ones to withstand the short, high-speed acceleration of earthquake shocks.

The Moon appears to turn red during a lunar eclipse due to dust and other pollutants in the atmosphere. ***© Y. Shopov. Reproduced by permission.***

Giant coronal streamers, visible only from space or the upper stratosphere during an eclipse. ***© Y. Shopov. Reproduced by permission.***

See also Convergent plate boundary; Earth, interior structure; Faults and fractures; Mid-plate earthquakes; Plate tectonics; Tsunami

EARTHQUAKE PREDICTION, ADVANCES IN RESEARCH • *see* SEISMOLOGY

ECLIPSE

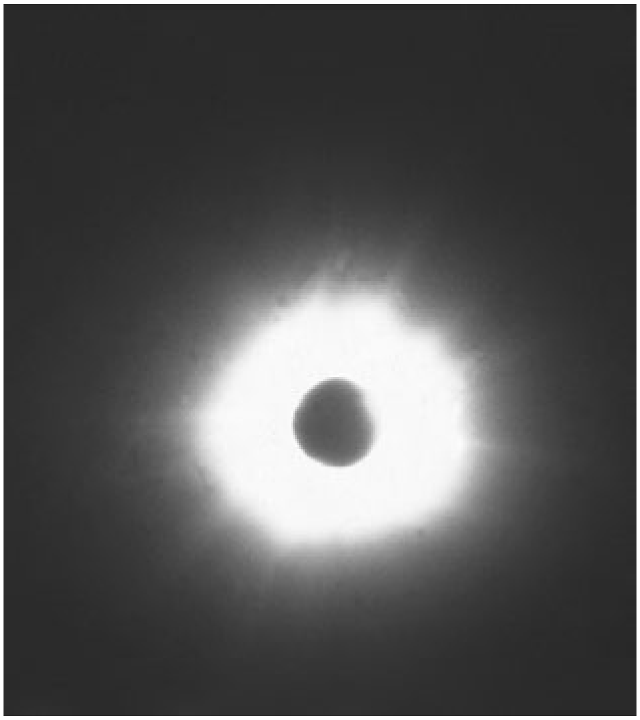
An eclipse is a phenomenon in which the light from a celestial body is temporarily obscured by the presence of another.

A solar eclipse occurs when the **Moon** is aligned between the **Sun** and Earth. The trace of the lunar shadow (where the solar eclipse is visible) is less than 270 km (168 mi) wide. A partial eclipse is visible over a much wider region. When the Moon is further away from Earth, the lunar disc has a smaller visible diameter than the solar disc, so a narrow ring of the Sun remains uncovered, even when the three bodies are aligned. This produces an annular solar eclipse. The ratio between the visible lunar and solar diameters is called the magnitude of the eclipse. At the beginning of the solar eclipse, the Moon progressively covers the solar disk. Illumination of Earth's surface rapidly diminishes. The air **temperature** falls a few degrees. Seconds before the totality of the eclipse, shadow bands appear. Shadow bands are irregular bands of shadow, a few centimeters wide and up to a meter apart, moving over the ground. The **diamond** ring phase of the eclipse then shines for few seconds and later, Bailey's beads appear on the solar limb. Bailey's beads are a string of bright beads of light produced by the uneven shape of the lunar limb.

In the first two to three seconds of the total phase of the eclipse (totality), the chromosphere is visible as a pink halo around half of the limb. Maximal duration of the totality varies from eclipse to eclipse, up to 7.5 minutes. The brightest stars and planets are observable on the sky during the totality. Prominences are the brightest objects visible continuously during the totality. They are **clouds** of relatively cold (10,000 K) and dense matter with the same properties as that of the chromosphere matter. They emit in lines of hydrogen, helium and calcuim, which produce the pink color of prominences and the chromosphere, and can always be observed in monochromatic light.

White corona can be observed from Earth only during total solar eclipses, because its intensity is much lower than the brightness of the sky. It has several components emitting in the entire visible region of spectra. The K- (Electron or continuum) corona is due to scattering of sunlight on free high-energy electrons, which are at a temperature of 1 million degrees, and contain continuous spectra and linear polarization of the light. The K-corona dominates in the corona, have distinct 11-year cycles, and have variable structures depending on the level of solar activity. During the solar maximum, it is circular. During the solar minimum, it is symmetrical and elongated in the equatorial region, while

Solar protuberances at high magnification, as seen during a total eclipse. © *Y. Shopov. Reproduced by permission.*



Far solar corona as seen during a total eclipse. © *Y. Shopov. Reproduced by permission.*

in the polar regions, it has bunches of short rays or plumes. During intermediate phases, it has asymmetric structure with many streamers of different lengths. The F- (Fraunhofer or Dust) corona is due to scattering of sunlight on dust particles. An F-corona has Fraunhofer spectra with absorption lines. Due to heating of dust particles close to the Sun, the F-corona evaporates, producing a large cavity in the dust distribution. An F-corona has oval shape. Its intensity decreases slowly with the distance from the Sun, and it predominates over the K-corona at long distances. The F-corona reaches near-Earth **space**, producing Zodiacal light (a faint conical glow extending along the ecliptic, visible after sunset or before sunrise in a dark, clear sky). The Thermal (T) corona is due to thermal emission of dust particles heated by the Sun.

Solar corona also have components emitting linear spectrum. The E- (Emission) corona is due to emission lines of highly ionized atoms of **iron**, nickel, and calcium. The E-corona intensity decreases rapidly with its distance from the Sun and is visible up to a 2-solar radius in monochromatic light. The S- (Sublimation) corona, was recently found, but as of 2002, its existence is still debatable. It consists of emission of low ionized atoms of Ca(II) produced by sublimation of dust particles in relatively cold parts of the corona. All these components are visible together in the corona during total eclipses.

The last and most mysterious component of the corona is giant coronal streamers observed only from the orbital coronagraph LASCO and from stratospheric flights during total eclipses. The giant coronal streamer shape and properties are different from those of any other component of the corona. Animations of their timed development look similar to visualizations of gusts of solar **wind**. In the last few years, evidence has arisen demonstrating that its nature is the same as that of plasma tails of **comets**, fluorescence of ionized gas molecules (originated by **evaporation** of comets near the Sun), and is due to interaction with the solar wind and sunlight. This component of the corona is called Fluorescent (Fl) corona, but this hypothesis needs further scientific verification. The corona is divided arbitrarily to Internal corona (up to 1.3 radius), which can be observed any time by coronagraph, Medium (1.3- 2.3 radius), and External corona (over 2.3 radius) where F-corona dominates. Edges of the corona gradually disappear in the background of the sky. Therefore, the size of the corona greatly depends on the spectral region of observations and clearness of the sky.

Lunar eclipses occur when the Moon passes into Earth's shadow. The Moon does not normally disappear completely; its disc is illuminated by light scattered by the Earth's atmosphere. Color of the lunar eclipse depends highly on the composition of the atmosphere (amount of **ozone** and dust). The full shadow (umbra) cast by Earth is surrounded by a region of partial shadow, called the penumbra. Some lunar eclipses are visible only as penumbral, other as partial. The length of the Moon's path through the umbra, divided by the Moon's diameter, defines the magnitude of a lunar eclipse.

See also Coronal ejections and magnetic storms

EINSTEIN, ALBERT (1879-1955)

German-born American physicist

Albert Einstein ranks as one of the most remarkable theoreticians in the history of science. He was also a heartfelt pacifist dedicated to world peace. During a single year, 1905, he produced three papers that are among the most important in twentieth-century **physics**, and perhaps in all of the recorded history of science, for they revolutionized the way scientists looked at the nature of **space**, time, and matter. These papers dealt with the nature of particle movement known as Brownian motion, the quantum nature of electromagnetic radiation as demonstrated by the photoelectric effect, and the special theory of relativity. Although Einstein is probably best known for the last of these works, it was for his quantum explanation of the photoelectric effect that he was awarded the 1921 Nobel Prize in physics. In 1915, Einstein extended his special theory of relativity to include certain cases of accelerated motion, resulting in the more general theory of relativity.

Einstein was born in Ulm, Germany, the only son of Hermann and Pauline Koch Einstein. Both sides of his family had long-established roots in southern Germany, and, at the time of Einstein's birth, his father and uncle Jakob owned a small electrical equipment plant. When that business failed around 1880, Hermann Einstein moved his family to Munich to make a new beginning. A year after their arrival in Munich, Einstein's only sister, Maja, was born.

Although his family was Jewish, Einstein was sent to a Catholic elementary school from 1884 to 1889. He was then enrolled at the Luitpold Gymnasium in Munich. During these years, Einstein began to develop some of his earliest interests in science and mathematics, but he gave little outward indication of any special aptitude in these fields. Indeed, he did not begin to talk until the age of three and, by the age of nine, was still not fluent in his native language.

In 1894, Hermann Einstein's business failed again, and the family moved once more, this time to Pavia, near Milan, Italy. Einstein was left behind in Munich to allow him to finish school. Such was not to be the case, however, since he left the *gymnasium* after only six more months. Einstein's biographer, Philipp Frank, explains that Einstein so thoroughly despised formal schooling that he devised a scheme by which he received a medical excuse from school on the basis of a potential nervous breakdown. He then convinced a mathematics teacher to certify that he was adequately prepared to begin his college studies without a high school diploma. Other biographies, however, say that Einstein was expelled from the *gymnasium* on the grounds that he was a disruptive influence at the school.

In any case, Einstein then rejoined his family in Italy. One of his first acts upon reaching Pavia was to give up his German citizenship. He was so unhappy with his native land that he wanted to sever all formal connections with it; in addition, by renouncing his citizenship, he could later return to Germany without being arrested as a draft dodger. As a result, Einstein remained without an official citizenship until he became a Swiss citizen at the age of 21. For most of his first year in Italy, Einstein spent his time traveling, relaxing, and teaching himself calculus and higher mathematics. In 1895, he thought himself ready to take the entrance examination for the Eidgenössiche Technische Hochschule (the ETH, Swiss Federal Polytechnic School, or Swiss Federal Institute of Technology), where he planned to major in electrical engineering. When he failed that examination, Einstein enrolled at a Swiss cantonal high school in Aarau. He found the more democratic style of instruction at Aarau much more enjoyable than his experience in Munich and soon began to make rapid progress. He took the entrance examination for the ETH a second time in 1896, passed, and was admitted to the school. (In *Einstein*, however, Jeremy Bernstein writes that Einstein was admitted without examination on the basis of his diploma from Aarau.)

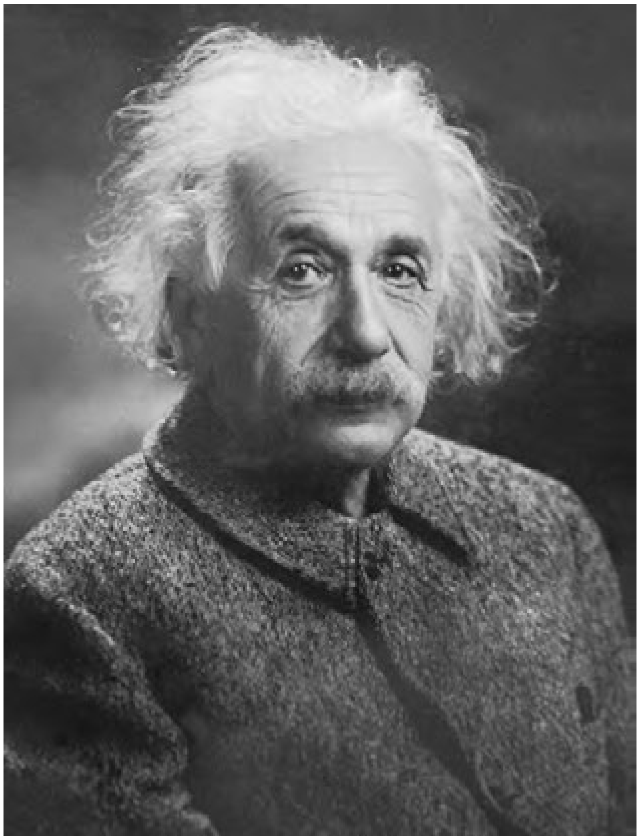
The program at ETH had nearly as little appeal for Einstein as had his schooling in Munich, however. He apparently hated studying for examinations and was not especially interested in attending classes on a regular basis. He devoted much of this time to reading on his own, specializing in the works of Gustav Kirchhoff, Heinrich Hertz, **James Clerk Maxwell**, Ernst Mach, and other classical physicists. When Einstein graduated with a teaching degree in 1900, he was unable to find a regular teaching job. Instead, he supported himself as a tutor in a private school in Schaffhausen. In 1901, Einstein also published his first scientific paper, "Consequences of Capillary Phenomena."

In February, 1902, Einstein moved to Bern and applied for a job with the Swiss Patent Office. He was given a probationary appointment to begin in June of that year and was promoted to the position of technical expert, third class, a few months later. The seven years Einstein spent at the Patent Office were the most productive years of his life. The demands of his work were relatively modest and he was able to devote a great deal of time to his own research.

The promise of a steady income at the Patent Office also made it possible for Einstein to marry. Mileva Maric (also given as Maritsch) was a fellow student in physics at ETH, and Einstein had fallen in love with her even though his parents strongly objected to the match. Maric had originally come from Hungary and was of Serbian and Greek Orthodox heritage. The couple married in 1903, and later had two sons, Hans Albert and Edward.

In 1905, Einstein published a series of papers, any one of which would have assured his fame in history. One, "On the Movement of Small Particles Suspended in a Stationary Liquid Demanded by the Molecular-Kinetic Theory of Heat," dealt with a phenomenon first observed by the Scottish botanist Robert Brown in 1827. Brown had reported that tiny particles, such as dust particles, move about with a rapid and random zigzag motion when suspended in a liquid.

Einstein hypothesized that the visible motion of particles was caused by the random movement of molecules that make up the liquid. He derived a mathematical formula that predicted the distance traveled by particles and their relative speed. This formula was confirmed experimentally by the French physicist Jean Baptiste Perrin in 1908. Einstein's work on the Brownian movement is generally regarded as the first direct experimental evidence of the existence of molecules.



Albert Einstein. ***Library of Congress.***

A second paper, "On a Heuristic Viewpoint concerning the Production and Transformation of Light," dealt with another puzzle in physics, the photoelectric effect. First observed by Heinrich Hertz in 1888, the photoelectric effect involves the release of electrons from a metal that occurs when light is shined on the metal. The puzzling aspect of the photoelectric effect was that the number of electrons released is not a function of the light's intensity, but of the color (that is, the wavelength) of the light.

To solve this problem, Einstein made use of a concept developed only a few years before, in 1900, by the German physicist **Max Planck**, the quantum hypothesis. Einstein assumed that light travels in tiny discrete bundles, or "quanta," of energy. The energy of any given light quantum (later renamed the photon), Einstein said, is a function of its wavelength. Thus, when light falls on a metal, electrons in the metal absorb specific quanta of energy, giving them enough energy to escape from the surface of the metal. But the number of electrons released will be determined not by the number of quanta (that is, the intensity) of the light, but by its energy (that is, its wavelength). Einstein's hypothesis was confirmed by several experiments and laid the foundation for the fields of quantitative photoelectric **chemistry** and quantum mechanics. As recognition for this work, Einstein was awarded the 1921 Nobel Prize in physics.

A third 1905 paper by Einstein, almost certainly the one for which he became best known, details his special theory of relativity. In essence, "On the Electrodynamics of Moving Bodies" discusses the relationship between measurements made by observers in two separate systems moving at constant velocity with respect to each other.

Einstein's work on relativity was by no means the first in the field. The French physicist Jules Henri Poincaré, the Irish physicist George Francis FitzGerald, and the Dutch physicist Hendrik Lorentz had already analyzed in some detail the problem attacked by Einstein in his 1905 paper. Each had developed mathematical formulas that described the effect of motion on various types of measurement. Indeed, the record of pre-Einstein thought on relativity is so extensive that one historian of science once wrote a two-volume work on the subject that devoted only a single sentence to Einstein's work. Still, there is little question that Einstein provided the most complete analysis of this subject. He began by making two assumptions. First, he said that the laws of physics are the same in all frames of reference. Second, he declared that the velocity of light is always the same, regardless of the conditions under which it is measured.

Using only these two assumptions, Einstein proceeded to uncover an unexpectedly extensive description of the properties of bodies that are in uniform motion. For example, he showed that the length and mass of an object are dependent upon their movement relative to an observer. He derived a mathematical relationship between the length of an object and its velocity that had previously been suggested by both FitzGerald and Lorentz. Einstein's theory was revolutionary, for previously scientists had believed that basic quantities of measurement such as time, mass, and length were absolute and unchanging. Einstein's work established the opposite—that these measurements could change, depending on the relative motion of the observer.

In addition to his masterpieces on the photoelectric effect, Brownian movement, and relativity, Einstein wrote two more papers in 1905. One, "Does the Inertia of a Body Depend on Its Energy Content?" dealt with an extension of his earlier work on relativity. He came to the conclusion in this paper that the energy and mass of a body are closely interrelated. Two years later he specifically stated that relationship in a formula, $E=mc^2$ (energy equals mass times the speed of light squared), that is now familiar to both scientists and non-scientists alike. His final paper, the most modest of the five, was "A New De Determination of Molecular Dimensions." It was this paper that Einstein submitted as his doctoral dissertation, for which the University of Zurich awarded him a Ph.D. in 1905.

Fame did not come to Einstein immediately as a result of his five 1905 papers. Indeed, he submitted his paper on relativity to the University of Bern in support of his application to become a *privatdozent*, or unsalaried instructor, but the paper and application were rejected. His work was too important to be long ignored, however, and a second application three years later was accepted. Einstein spent only a year at Bern, however, before taking a job as professor of physics at the University of Zurich in 1909. He then went on to the German University of Prague for a year and a half before returning to Zurich and a position at ETH in 1912. A year later Einstein was made director of scientific research at the Kaiser Wilhelm Institute for Physics in Berlin, a post he held from 1914 to 1933.

Einstein was increasingly occupied with his career and his wife with managing their household; upon moving to Berlin in 1914, the couple grew distant. With the outbreak of World War I, Einstein's wife and two children returned to Zurich. The two were never reconciled; in 1919, they were formally divorced. With the outbreak of the war, Einstein's pacifist views became public knowledge. When 93 leading German intellectuals signed a manifesto supporting the German war effort, Einstein and three others published an antiwar counter-manifesto. He also helped form a coalition aimed at fighting for a just peace and for a worldwide organization to prevent future wars. Towards the end of the war, Einstein became very ill and was nursed back to health by his cousin Elsa. Not long after Einstein's divorce from Maric, he was married to Elsa, a widow. The two had no children of their own, although Elsa brought two daughters to the marriage.

The war years also marked the culmination of Einstein's attempt to extend his 1905 theory of relativity to a broader context, specifically to systems with non-zero acceleration. Under the general theory of relativity, motions no longer had to be uniform and relative velocities no longer constant. Einstein was able to write mathematical expressions that describe the relationships between measurements made in any two systems in motion relative to each other, even if the motion is accelerated in one or both. One of the fundamental features of the general theory is the concept of a space-time continuum in which space is curved. That concept means that a body affects the shape of the space that surrounds it so that a second body moving near the first body will travel in a curved path.

Einstein's new theory was too radical to be immediately accepted, for not only were the mathematics behind it extremely complex, it replaced Newton's theory of gravitation that had been accepted for two centuries. So, Einstein offered three proofs for his theory that could be tested: first, that relativity would cause Mercury's perihelion, or point of orbit closest to the **sun**, to advance slightly more than was predicted by Newton's laws. Second, Einstein predicted that light from a star would be bent as it passes close to a massive body, such as the sun. Last, the physicist suggested that relativity would also affect light by changing its wavelength, a phenomenon known as the redshift effect. Observations of the planet Mercury bore out Einstein's hypothesis and calculations, but astronomers and physicists had yet to test the other two proofs.

Einstein had calculated that the amount of light bent by the sun would amount to 1.7 seconds of an arc, a small but detectable effect. In 1919, during an **eclipse** of the sun, English astronomer Arthur Eddington measured the deflection of starlight and found it to be 1.61 seconds of an arc, well within experimental error. The publication of this proof made Einstein an instant celebrity and made "relativity" a household word, although it was not until 1924 that Eddington proved the final hypothesis concerning redshift with a spectral analysis of the star Sirius B. Thus, it was proved that light would be shifted to a longer wavelength in the presence of a strong gravitational field.

Einstein's publication of his general theory in 1916, the *Foundation of the General Theory of Relativity*, essentially brought to a close the revolutionary period of his scientific career. In many ways, Einstein had begun to fall out of phase with the rapid changes taking place in physics during the 1920s. Even though Einstein's own work on the photoelectric effect helped set the stage for the development of **quantum theory**, he was never able to accept some of its concepts, particularly the uncertainty principle. In one of the most-quoted comments in the history of science, he claimed that quantum mechanics, which could only calculate the probabilities of physical events, could not be correct because "God does not play dice." Instead, Einstein devoted his efforts for the remaining years of his life to the search for a unified field theory, a single theory that would encompass all physical fields, particularly gravitation and electromagnetism.

In early 1933, Einstein made a decision. He was out of Germany when Hitler rose to power, and he decided not to return. In March 1933, he again renounced his German citizenship. His remaining property in German was confiscated and his name appeared on the first Nazi list of those who were stripped of citizenship. He accepted an appointment at the Institute for Advanced Studies in Princeton, New Jersey, where he spent the rest of his life. In addition to his continued work on unified field theory, Einstein was in demand as a speaker and wrote extensively on many topics, especially peace.

The growing fascism and anti-Semitism of Hitler's regime, however, convinced him in 1939 to sign his name to a letter written by American physicists warning President Franklin D. Roosevelt that the Germans were nearing the possibility of an atomic bomb, and that Americans must develop the technology first. This letter led to the formation of the Manhattan Project for the construction of the world's first nuclear weapons. Although Einstein's work on relativity, particularly his formulation of the equation $E=mc^2$, was essential to the development of the atomic bomb, Einstein himself did not participate in the project. He was considered a security risk, although he had renounced his German citizenship and become a U.S. citizen in 1940, while retaining his Swiss citizenship.

In 1944, he contributed to the war effort by hand writing his 1905 paper on special relativity, and putting it up for auction. The manuscript, which raised $6 million, is today the property of the U.S. Library of Congress.

After World War II and the bombing of Japan, Einstein became an ardent supporter of nuclear disarmament. He continued to support the efforts to establish a world government and the Zionist movement to establish a Jewish state. In 1952, after the death of Israel's first president, Chaim Weizmann, Einstein was invited to succeed him as president; he declined the offer.

Among the many other honors given to Einstein were the Barnard Medal of Columbia University in 1920, the Copley Medal of the Royal Society in 1925, the Gold Medal of the Royal Astronomical Society in 1926, the Max Planck Medal of the German Physical Society in 1929, and the Franklin Medal of the Franklin Institute in 1935. He also received honorary doctorates in science, medicine and philosophy from many

European and American universities and was elected to memberships in all of the leading scientific academies in the world. In December 1999, *Time* magazine named Einstein "Person of the Century," stating: "In a hundred years, as we turn to another new century—nay, ten times a hundred years, when we turn to another new millennium—the name that will prove most enduring from our own amazing era will be that of Albert Einstein: genius, political refugee, humanitarian, locksmith of the mysteries of the **atom** and the universe."

A week before he died, Einstein agreed to include his name on a manifesto urging all nations to give up nuclear weapons. Einstein died in his sleep at his home in Princeton at the age of 76, after suffering an aortic aneurysm. At the time of his death, he was the world's most widely admired scientist and his name was synonymous with genius. Yet Einstein declined to become enamored of the admiration of others. He wrote in his book *The World as I See It*: "Let every man be respected as an individual and no man idolized. It is an irony of fate that I myself have been the recipient of excessive admiration and respect from my fellows through no fault, and no merit, of my own. The cause of this may well be the desire, unattainable for many, to understand the one or two ideas to which I have with my feeble powers attained through ceaseless struggle."

See also History of exploration III (Modern era); Relativity theory

EIS (ENVIRONMENTAL IMPACT STATEMENT)

Societies are attempting to develop means of coping with the environmental stressors caused by human activities. These include the activities of individual people as they go about their daily lives, as well as the larger enterprises of corporations, governments, and society at large. One of the procedures that is increasingly becoming a routine component of planning for potential damages is known as environmental impact assessment.

The environmental impact assessment (EIA), and the subsequently prepared statement (EIS), is a process that can be used to identify and estimate the potential environmental consequences of proposed developments and policies. Environmental impact assessment is a highly interdisciplinary process, involving inputs from many fields in the sciences and social sciences. Environmental impact assessments commonly examine ecological, physical/chemical, sociological, economic, and other environmental effects.

Environmental assessments may be conducted to review the potential effects of: (1) individual projects, such as the construction of a particular power plant, incinerator, airport, or housing development; (2) integrated development schemes, or proposals to develop numerous projects in some **area**. Examples include an industrial park, or an integrated venture to harvest, manage, and process a natural resource, such as a pulp mill with its associated wood-supply and forest-management plans; or (3) government policies that carry a risk of having substantial environmental effects. Examples include decisions to give national priority to the generation of **electricity** using nuclear reactors, or to clear large areas of natural forest to develop new lands for agricultural use.

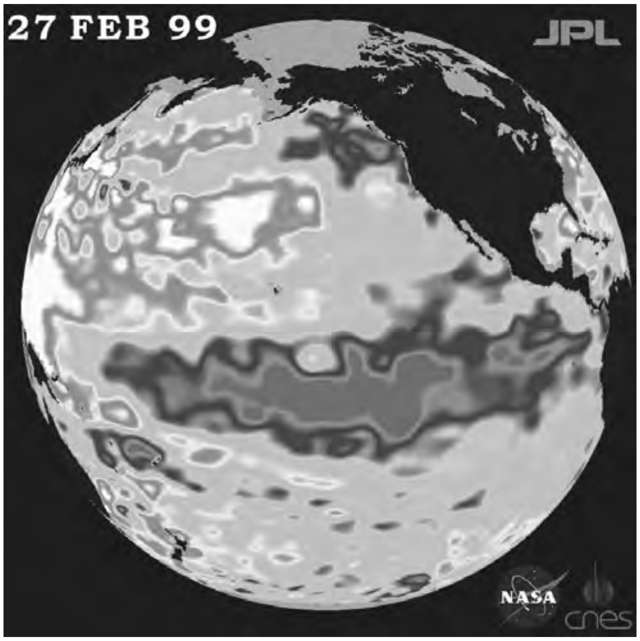
An extraordinary variety of environmental and ecological changes can potentially be caused by any project, scheme, or policy. Consequently, it is never practical in an environmental impact assessment to consider all of the potential effects of a proposal. Usually certain indicators, called "valued ecosystem components" (VECs), are carefully selected for study, on the basis of their importance to society. The valued ecosystem components are often identified through consultations with representatives of regulatory agencies, scientists, non-governmental organizations, and the public.

Examples of commonly examined VECs include: (1) resources that are economically important, such as agricultural or forest productivity, and populations of hunted fish or game; (2) rare or endangered species and natural ecosystems; (3) particular species, communities, or landscapes that are of cultural or aesthetic importance; and (4) simple indicators of a complex of ecological values. The spotted owl, for example, is an indicator of the integrity of certain types of old-growth conifer **forests** in western **North America**. Any proposed activity, likely associated with forestry, that threatens a population of these birds also indicates a challenge to the larger, old-growth forest ecosystem.

The initial phase of an environmental impact assessment attempts to screen for potentially important conflicts between proposed activities and valued ecosystem components. Essentially, this is done by predicting the dimensions in **space** and time of stressors associated with the proposed development, and then comparing these with the known boundaries of VECs. This is a preliminary, scoping exercise, which may require environmental scientists to make professional judgments about the severity and importance of potential interactions between stressors and VECs. The best-available information is used to guide these interpretations, although the existing knowledge is almost always incomplete. To better determine the risks of interactions identified during the preliminary screening, it is highly desirable to undertake field, laboratory, or simulation research. However, time and funds are not always available to support new research, and this can constrain some impact assessments.

Once potentially important risks to VECs are identified and studied, it is possible to consider various planning options. During this stage of the impact assessment, environmental specialists provide objective information and their professional opinions to decision makers, who must then make choices that deal with the conflicts. There are three broad types of choices that can be made:

(1) The predicted damages can be avoided, by not proceeding with the development, or by modifying its structure. However, avoidance is often considered an undesirable option by proponents of a development. This is because irreconcilable conflicts with environmental quality can result in substantial costs, including canceled projects. Regulators and politicians also tend to resent this option, because socioeconomic opportunities can be lost, and there is often intense controversy.



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. ***TOPEX/Poseidon, NASA JPL.***

False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. ***TOPEX/Poseidon, NASA JPL.***

(2) Often, mitigations can be designed and implemented to prevent or significantly reduce damages to the VEC. For example: (a) if an industrial activity is predicted to acidify a lake, an appropriate mitigation might be liming to reduce the acidification; (b) if habitat of an endangered species is threatened, the risk may be mitigated by moving the population to another site; or (c) the emissions of **carbon dioxide** from a proposed coal-fired generating station could be offset by planting trees to achieve no net change in atmospheric concentrations of this gas. Mitigations are common ways of resolving conflicts between project-related stressors and VECs. However, there are always substantial risks with the use of mitigations, because ecological and environmental knowledge are incomplete, and it is not necessarily known if mitigations will actually work properly to protect the VEC.

(3) Another option that is often selected is to allow the damages to the VEC to occur, and to accept the degradation as an unfortunate cost of achieving the perceived socioeconomic benefits of proceeding with the development. This choice is common, because not all environmental damages can be avoided or mitigated, and many damaging activities can yield large, short-term profits.

It is not possible to carry out large industrial or economic developments without causing some environmental damages. However, a properly done impact assessment can help decision makers to understand the dimensions and importance of those damages, and to decide whether they are acceptable, or whether they must be reduced or avoided.

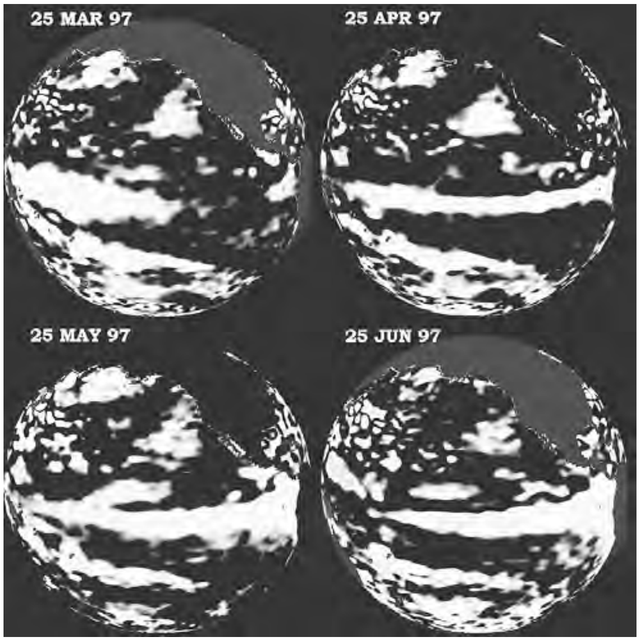
See also Earth (planet); Earth science

EL NIÑO AND LA NIÑA PHENOMENA

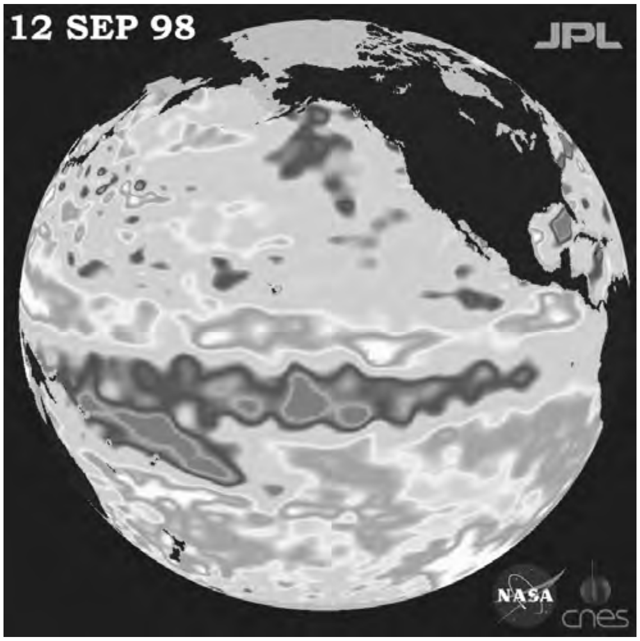
El Niño and La Niña are the names given to changes in the winds, **atmospheric pressure**, and seawater that occur in the Pacific Ocean near the equator. El Niño and La Niña are opposite phases of a back and forth cycle in the Pacific Ocean and the atmosphere above it. Unlike winter and summer, however, El Niño and La Niña do not change with the regularity of the **seasons**; instead, they repeat on average about every three or four years. They are the extremes in a vast repeating cycle called the Southern Oscillation, El Niño being the warm extreme and La Niña the cold extreme.

Although El Niño and La Niña take place in a small portion of the Pacific, the changes caused by Southern Oscillation can affect the **weather** in large parts of **Asia**, **Africa**, Indonesia and North and **South America**. Scientists have only recently become aware of the far-reaching effects of the Southern Oscillation on the world's weather. An El Niño during 1982–83 was associated with record snowfall in parts of the Rocky Mountains, flooding in the southern United States, and heavy rain storms in southern California, which brought about **floods** and mud slides.

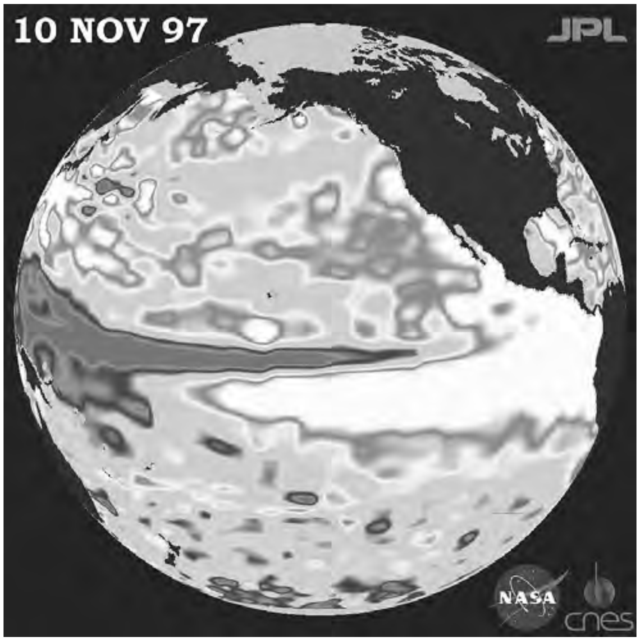
The name El Niño comes from Peruvian fishermen. They noticed that near the end of each year, the seawater off the South American coast became warmer, which made fishing much poorer. Because the change appeared each year close to Christmas, the fishermen dubbed it El Niño, Spanish for "the boy child" referring to the Christ child. Every few years, the changes brought with El Niño were particularly strong or long lasting. During these strong El Niños, the warmer sea waters nearly wiped out fishing and brought sig-



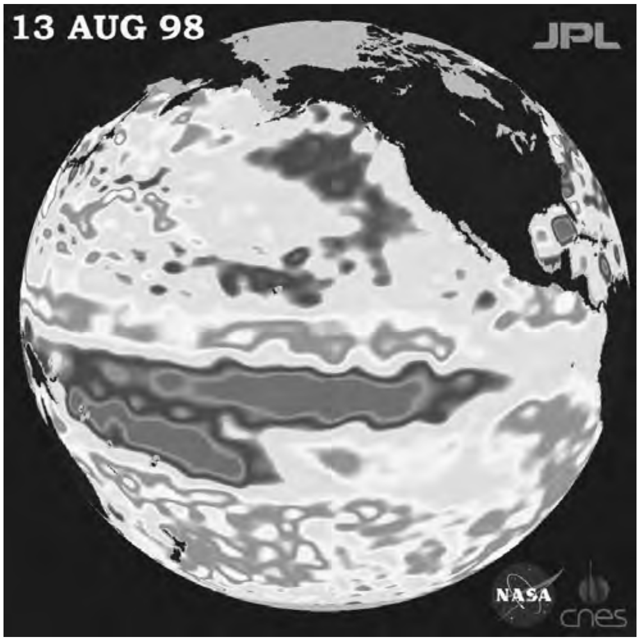
Four false color views of ocean surface height of the Pacific Ocean, with red and white areas showing increased heat storage. *TOPEX/Poseidon, NASA JPL.*



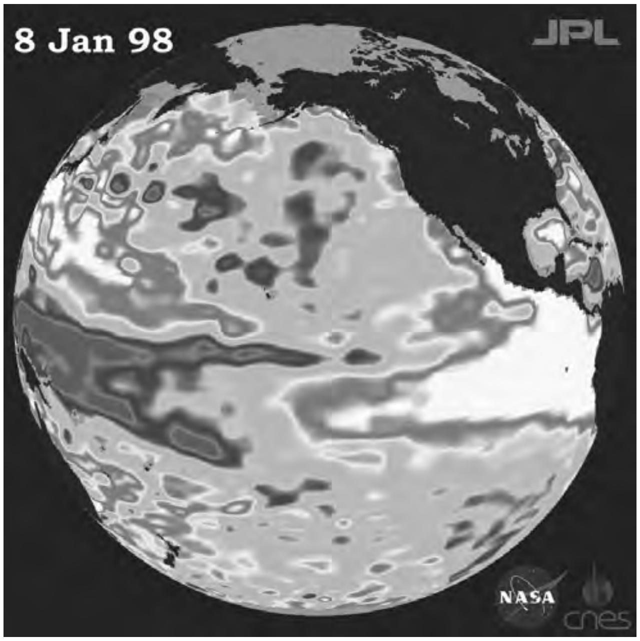
False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. *TOPEX/Poseidon, NASA JPL.*



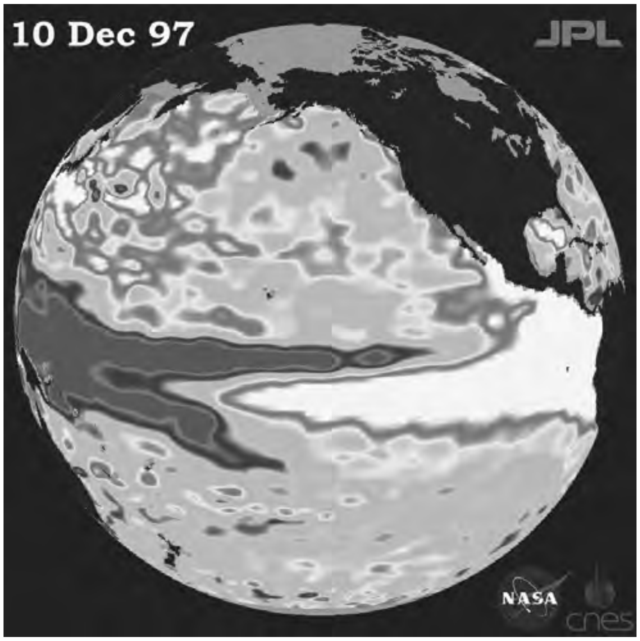
False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. *TOPEX/Poseidon, NASA JPL.*



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. *TOPEX/Poseidon, NASA JPL.*



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. ***TOPEX/Poseidon, NASA JPL.***



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. ***TOPEX/Poseidon, NASA JPL.***

nificant changes in weather. For example, normally dry areas on shore could receive abundant rain, turning deserts into lush grasslands for as long as these strong El Niños lasted. In the 1950s and 60s it was found that strong El Niños were associated with increased sea surface temperatures throughout the eastern tropical Pacific. In recent years, these strong El Niños have been recognized as not just a local change in the sea, but as one half of a vast atmospheric-oceanic cycle.

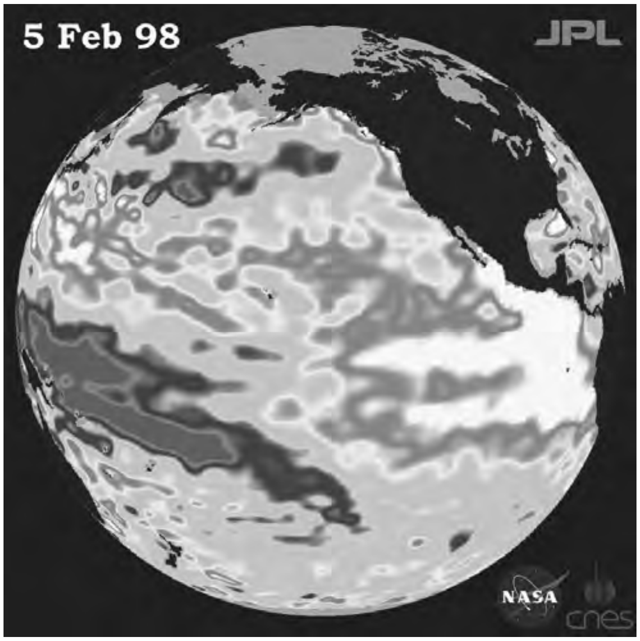
The other half of the repeating cycle has been named La Niña, or the girl child. This phase of the Southern Oscillation is also sometimes called El Viejo, or the old man.

The Southern Oscillation was detected in the early 1920s by Sir Gilbert Walker. He was trying to understand the variations in the summer monsoons (rainy seasons) of India by studying the way atmospheric pressure changed over the Pacific Ocean. Based on meteorologists' previous pressure observations from many stations in the southern Pacific and Indian **oceans**, Walker established that over the years, atmospheric pressure seesawed back and forth across the ocean. In some years, pressure was highest over northern **Australia** and lowest over the southeastern Pacific, near the island of Tahiti. In other years, the pattern was reversed. The two pressure patterns had specific weather patterns associated with each, and the change from one phase to the other could mean the shift from rainfall to **drought**, or from good harvests to famine. In the late 1960s, Jacob Bjerknes, a professor at the University of California, first proposed that the Southern Oscillation and the strong El Niño sea warming were two aspects of the same vast atmosphere-ocean cycle.

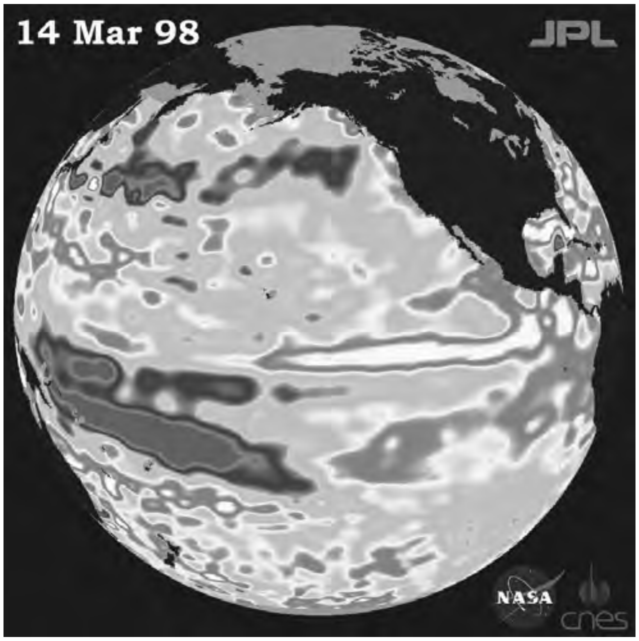
El Niño and the Southern Oscillation (often referred to as ENSO) take place in the tropics, a part of the world dominated by prevailing winds, called the trade winds. Near the equator in the tropical Pacific, these easterly (east to west) winds blow day in and day out and tend to pull the surface **water** of the ocean along with them. This pulls the warm surface water westward, where it collects on the western edge of the ocean basin, the **area** that includes Indonesia, eastern Australia and many Pacific Islands. The warm waters literally pile up in these areas, where the sea level is about 16 inches (40 cm) higher than in the eastern Pacific.

Meanwhile, along the coast of South America colder water from the ocean depths rises to the top, since the warmer water has been blown westward. The result is called upwelling, and it occurs along much of the coasts of South and **North America**. Upwelling has two important consequences. The cold deep waters tend to have more nutrients than surface water; these nutrients are essential to phytoplankton, the tiny plants of the sea that provide food for many other types of sea life. Thus, upwelling zones are very productive for fish and the animals (and people) that depend on fish for food. The second result of upwelling cold water is that it cools the air above it. Cool air is denser than warm air, and cool air in the atmosphere cannot begin rising to form **clouds** and thunderstorms. As a result, the areas near upwelling zones tend to be arid (desert-like) because rain clouds rarely form.

The warmer water that builds up in the western Pacific warms the air above it. This warm moist air frequently rises to form clouds, which eventually produce rainfall. When the trade winds are blowing the warm water their way, the lands along the western Pacific enjoy abundant rainfall. Many rain



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. *TOPEX/Poseidon, NASA JPL.*



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. *TOPEX/Poseidon, NASA JPL.*

forests are found in these areas, such as those of Borneo and New Guinea.

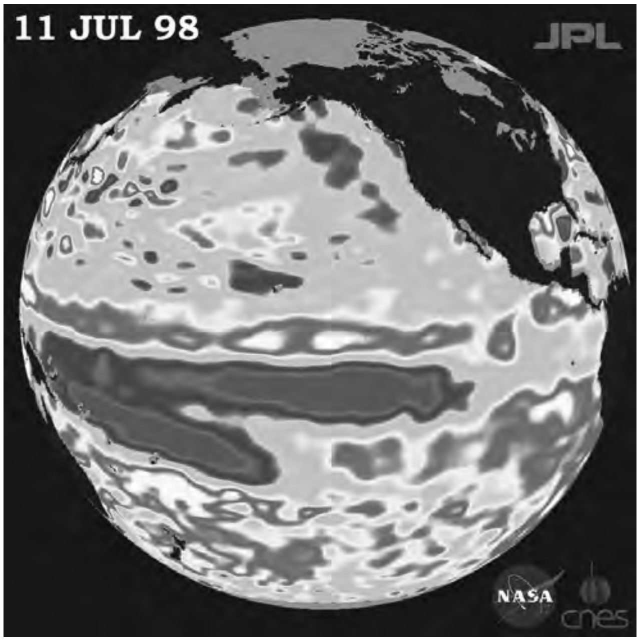
The pattern of winds described above is the La Niña phase of the Southern Oscillation. It sets up the areas of high and low atmospheric pressure observed by Walker and others: in the west, warm air rising produces low pressure, while farther east the cooler, denser air leads to areas of high pressure.

The atmosphere and the ocean form a system that is coupled, that is, they respond to each other. Changes in the ocean will cause a response in the winds above it, and vice versa. For reasons not yet fully understood, the coupled atmosphere-ocean system of the La Niña phase begins to change, slowly developing the characteristics of El Niño phase. The trade winds weaken somewhat, so that they pull less warm water to the western edge of the Pacific. This causes far-reaching changes. Fewer rain clouds form over the lands along the western Pacific. The lush rain forests dry out and become fuel for forest fires. The area of heavy rain shifts to the mid-southern Pacific, where formerly **desert** island are soaked day after day. In the eastern Pacific, the surface water becomes warmer, since it is no longer being driven westward. Ocean upwelling is weakened, so the water near the surface soon runs low on nutrients, which support the ocean food chain. Many species of fish are driven elsewhere to find food; in severe El Niño years fish populations may be almost completely wiped out. Bird species that depend on fish must look elsewhere, and the human fishing population face economic hardship. At the same time, the warmer waters offshore encourage the development of clouds and thunderstorms. Normally dry areas in western South America, such as Peru and Ecuador, may experience torrential rains and flooding during the El Niño phase.

While its effects have long been noted in the tropical Pacific, El Niño is now being studied for its impact on weather around the world. The altered pattern of winds and ocean temperatures during an El Niño is believed to change the high-level winds, called the jet streams, that steer storms over North and South America. El Niños have been linked with milder winters in western Canada and the northern United States, as most severe storms are steered northward to Alaska. As Californians saw in 1982-83, El Niño can cause extremely wet winters along the west coast, bringing torrential rains to the lowlands and heavy snow packs to the mountains. The jet streams altered by El Niño can also contribute to storm development over the **Gulf of Mexico**, which bring heavy rains to the southeastern United States. Similar changes occur in countries of South America, such as Chile and Argentina, while droughts may affect Bolivia and parts of Central America.

El Niño also appears to affect monsoons, which are annual shifts in the prevailing winds that bring on rainy seasons. The rains of the monsoon are critical for agriculture in India, Southeast Asia and portions of Africa; when the monsoon fails, millions of people are at risk of starvation. At present it appears that while El Niños do not always determine monsoons, they are associated with weakened monsoons in India and southeastern Africa, while tending to strengthen those in eastern Africa.

In general, the effects of El Niño are reversed during the La Niña extremes of the Southern Oscillation cycle. During the 1999 La Niña episode, for example, the central and north-



False color image of ocean surface height of the Pacific Ocean, with red and white showing increased heat storage, purple showing low sea level, and green showing normal conditions. ***TOPEX/Poseidon, NASA JPL.***

eastern United States experienced record snowfall and subzero temperatures, while rainfall increased in the Pacific Northwest and a record number of tornadoes plagued the southern states. Not all El Niños and La Niñas have equally strong effects on the global **climate** because every El Niño and La Niña event is of a different magnitude and duration.

The widespread weather impacts of the two extreme phases of the Southern Oscillation make their understanding and prediction a high priority for atmospheric scientists. Researchers have developed computer models of the Southern Oscillation that mimic the behavior of the real atmosphere-ocean system. These computer simulations require the input of mountains of data about sea and **wind** conditions in the equatorial Pacific. The measurements are provided by a large and growing network of instruments. Ocean buoys, permanently moored in place across the Pacific, constantly relay information on water **temperature**, wind, and air pressure to weather prediction stations around the world. The buoys are augmented by surface ships, island weather stations, and Earth observing satellites.

Even with mounting data and improving computer models, El Niño, La Niña and the Southern Oscillation remain difficult to predict. However, the Southern Oscillation models are now being used in several countries to help prepare for the next El Niño. Countries most affected by the variations in El Niño, such as Peru, Australia and India, have begun to use El Niño prediction to improve agricultural planning.

See also Air masses and fronts; Atmospheric circulation; Ocean circulation and currents

ELECTRICITY AND MAGNETISM

Electricity and **magnetism** are manifestations of a single underlying electromagnetic force. Electromagnetism is a branch of physical science that describes the interactions of electricity and magnetism, both as separate phenomena and as a singular electromagnetic force. A **magnetic field** is created by a moving electric current and a magnetic field can induce movement of charges (electric current). The rules of electromagnetism also explain geomagnetic and electromagnetic phenomena by explaining how charged particles of atoms interact.

Before the advent of technology, electromagnetism was perhaps most strongly experienced in the form of **lightning**, and electromagnetic radiation in the form of light. Ancient man kindled fires that he thought were kept alive in trees struck by lightning. Magnetism has long been employed for navigation in the compass. In fact, it is known that Earth's magnetic poles have exchanged positions in the past.

Some of the rules of *electrostatics*, the study of electric charges at rest, were first noted by the ancient Romans, who observed the way a brushed comb would attract particles. It is now known that electric charges occur in two different forms, positive charges and negative charges. Like charges repel each other, and differing types attract.

The force that attract positive charges to negative charges weakens with distance, but is intrinsically very strong—up to 40 times stronger than the pull of **gravity** at the surface of the earth. This fact can easily be demonstrated by a small magnet that can hold or suspend an object. The small magnet exerts a force at least equal to the pull of gravity from the entire Earth.

The fact that unlike charges attract means that most of this force is normally neutralized and not seen in full strength. The negative charge is generally carried by the atom's electrons, while the positive resides with the protons inside the atomic nucleus. Other less known particles can also carry charge. When the electrons of a material are not tightly bound to the atom's nucleus, they can move from **atom** to atom and the substance, called a conductor, can conduct electricity. Conversely, when the electron binding is strong, the material resists electron flow and is an insulator.

When electrons are weakly bound to the atomic nucleus, the result is a semiconductor, often used in the electronics industry. It was not initially known if the electric current carriers were positive or negative, and this initial ignorance gave rise to the convention that current flows from the positive terminal to the negative. In reality we now know that the electrons actually flow from the negative to the positive.

Electromagnetism is the theory of a unified expression of an underlying force, the electromagnetic force. This is seen in the movement of electric charge, that gives rise to magnetism (the electric current in a wire being found to deflect a compass needle), and it was Scottish physicist **James Clerk Maxwell** (1831–1879), who published a unifying theory of electricity and magnetism in 1865. The theory arose from former specialized work by German mathematician Carl Fredrich Gauss (1777–1855), French physicist Charles Augustin de Coulomb (1736–1806), French scientist André Marie Ampère

Electricity turns this large piece of metal into a powerful magnet, allowing scrap metal to be easily moved. © *Corbis/Bettmann. Reproduced by permission.*

(1775–1836), English physicist **Michael Faraday** (1791–1867), American scientist and statesman **Benjamin Franklin** (1706–1790), and German physicist and mathematician Georg Simon Ohm (1789–1854). However, one factor that did not contradict the experiments was added to the equations by Maxwell to ensure the conservation of charge. This was done on the theoretical grounds that charge should be a conserved quantity, and this addition led to the prediction of a wave phenomena with a certain anticipated velocity. Light, with the expected velocity, was found to be an example of this electromagnetic radiation.

Light had formerly been thought of as consisting of particles (photons) by Newton, but the theory of light as particles was unable to explain the wave nature of light (diffraction and the like). In reality, light displays both wave *and* particle properties. The resolution to this duality lies in **quantum theory**, where light is neither particles nor wave, but both. It propagates as a wave without the need of a medium and interacts in the manner of a particle. This is the basic nature of quantum theory.

Classical electromagnetism, useful as it is, contains contradictions (acausality) that make it incomplete and drive one to consider its extension to the **area** of quantum **physics**, where electromagnetism, of all the fundamental forces of nature, it is perhaps the best understood.

There is much symmetry between electricity and magnetism. It is possible for electricity to give rise to magnetism, and symmetrically for magnetism to give rise to electricity (as in the exchanges within an electric transformer). It is an exchange of just this kind that constitutes electromagnetic waves. These waves, although they don’t need a medium of propagation, are slowed when traveling through a transparent substance.

Electromagnetic waves differ from each other only in amplitude, frequency, and orientation (polarization). Laser beams are particular in being very coherent, that is, the radiation is of one frequency, and the waves coordinated in motion and direction. This permits a highly concentrated beam that is used not only for its cutting abilities, but also in electronic data storage, such as in CD-ROMs.

The differing frequency forms are given a variety of names, from radio waves at very low frequencies through light itself, to the high frequency x rays and gamma rays.

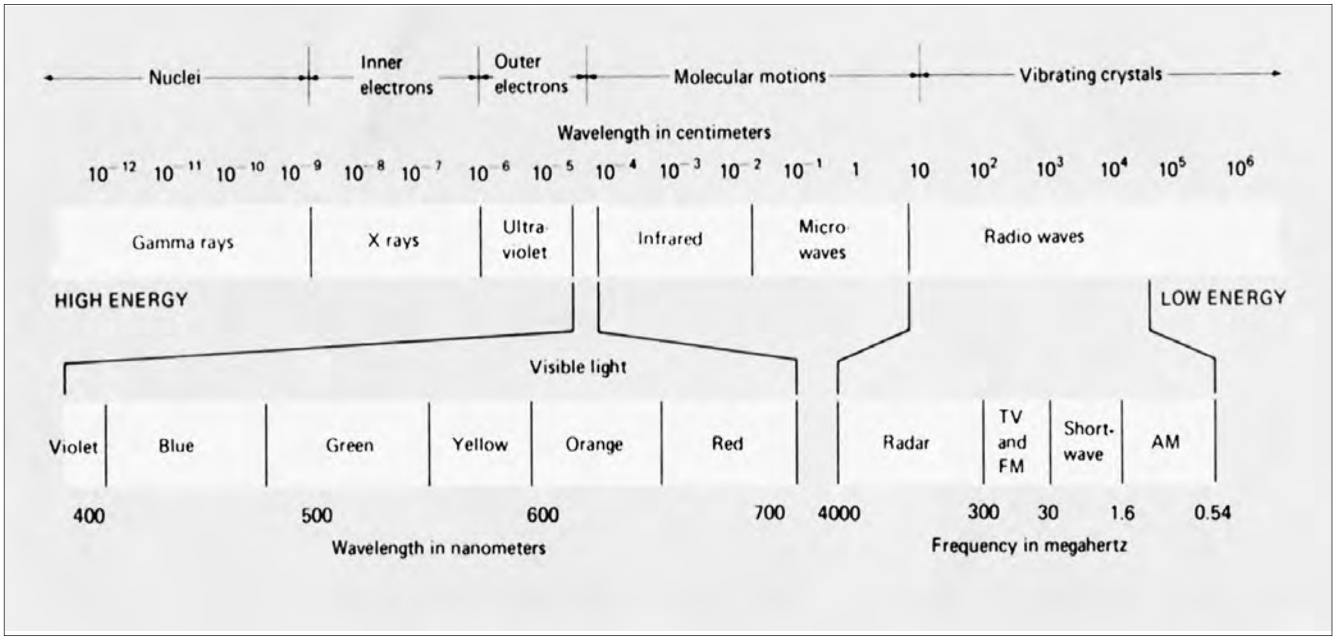
The unification of electricity and magnetism allows a deeper understanding of physical science, and much effort has been put into further unifying the four forces of nature (e.g., the electromagnetic, weak, strong, and gravitational forces. The weak force has now been unified with electromagnetism, called the electroweak force. There are research programs attempting to collect data that may lead to a unification of the strong force with the electroweak force in a grand unified theory, but the inclusion of gravity remains an open problem.

Maxwell’s theory is in fact in contradiction with Newtonian mechanics, and in trying to find the resolution to this conflict, Einstein was lead to his theory of special relativity. Maxwell’s equations withstood the conflict, but it was Newtonian mechanics that were corrected by relativistic mechanics. These corrections are most necessary at velocities, close to the speed of light.

Paradoxically, magnetism is a counter example to the frequent claims that relativistic effects are not noticeable for low velocities. The moving charges that compose an electric current in a wire might typically only be traveling at several feet per second (walking speed), and the resulting Lorentz contraction of special relativity is indeed minute. However, the electrostatic forces at balance in the wire are of such great magnitude, that this small contraction of the moving (negative) charges exposes a residue force of real world magnitude, namely the magnetic force. It is in exactly this way that the magnetic force derives from the electric. Special relativity is indeed hidden in Maxwell’s equations, which were known before special relativity was understood or separately formulated by Einstein.

Electricity at high voltages can carry energy across extended distances with little loss. Magnetism derived from that electricity can then power vast motors. But electromagnetism can also be employed in a more delicate fashion as a means of communication, either with wires (as in the telephone), or without them (as in radio communication). It also drives motors and provides current for electronic and computing devices.

See also Aurora Borealis and Aurora Australialis; Earth, interior structure; Electromagnetic spectrum; Ferromagnetic;



Spectrum of electromagnetic radiation. *Illustration by Robert L. Wolke. Reproduced by permission.*

Quantum electrodynamics (QED); Quantum theory and mechanics

ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum encompasses a continuous range of frequencies or wavelengths of electromagnetic radiation, ranging from long wavelength, low energy radio waves, to short wavelength, high frequency, high-energy gamma rays. The electromagnetic spectrum is traditionally divided into regions of radio waves, microwaves, infrared radiation, visible light, **ultraviolet rays**, x rays, and gamma rays.

Scottish physicist James Clerk Maxwell's (1831–1879) development of a set of equations that accurately described electromagnetic phenomena allowed the mathematical and theoretical unification of electrical and magnetic phenomena. When Maxwell's calculated speed of light fit well with experimental determinations of the speed of light, Maxwell and other physicists realized that visible light should be a part of a broader electromagnetic spectrum containing forms of electromagnetic radiation that varied from visible light only in terms of wavelength and wave frequency. Frequency is defined as the number of wave cycles that pass a particular point per unit time, and is commonly measured in Hertz (cycles per second). Wavelength defines the distance between adjacent points of the electromagnetic wave that are in equal phase (e.g., wavecrests).

Exploration of the electromagnetic spectrum quickly resulted practical advances. German physicist Henrich Rudolph Hertz regarded Maxwell's equations as a path to a "kingdom" or "great domain" of electromagnetic waves. Based on this insight, in 1888, Hertz demonstrated the existence of radio waves. A decade later, Wilhelm Röentgen's discovery of high-energy electromagnetic radiation in the form of x rays quickly found practical medical use.

At the beginning of the twentieth century, German physicist, Maxwell Planck, proposed that atoms absorb or emit electromagnetic radiation only in certain bundles termed quanta. In his work on the photoelectric effect, German-born American physicist **Albert Einstein** used the term photon to describe these electromagnetic quanta. Planck determined that energy of light was proportional to its frequency (i.e., as the frequency of light increases, so does the energy of the light). Planck's constant, h=6.626x10^{-34} joule-second in the meter-kilogram-second system, relates the energy of a photon to the frequency of the electromagnetic wave and allows a precise calculation of the energy of electromagnetic radiation in all portions of the electromagnetic spectrum.

Although electromagnetic radiation is now understood as having both photon (particle) and wave-like properties, descriptions of the electromagnetic spectrum generally utilize traditional wave-related terminology (i.e., frequency and wavelength).

Electromagnetic fields and photons exert forces that can excite electrons. As electrons transition between allowed orbitals, energy must be conserved. This conservation is achieved by the emission of photons when an electron moves from a higher potential orbital energy to a lower potential orbital energy. Accordingly, light is emitted only at certain frequencies characteristic of every **atom** and molecule. Correspondingly, atoms and molecules absorb only a limited range of frequencies and wavelengths of the electromagnetic spectrum, and reflect all the other frequencies and wavelengths of light. These reflected frequencies and wavelengths are often the actual observed light or colors associated with an object.

The region of the electromagnetic spectrum that contains light at frequencies and wavelengths that stimulate the rod and cones in the human eye is termed the visible region of the electromagnetic spectrum. Color is the association the eye makes with selected portions of that visible region (i.e., particular colors are associated with specific wavelengths of visible light). A nanometer (10^{-9} m) is the most common unit used for characterizing the wavelength of visible light. Using this unit, the visible portion of the electromagnetic spectrum is located between 380nm-750nm and the component color regions of the visible spectrum are: Red (670–770 nm), Orange (592–620 nm), Yellow (578–592 nm), Green (500–578 nm), Blue (464–500 nm), Indigo (444–464 nm), and Violet (400–446 nm). Because the energy of electromagnetic radiation (i.e., the photon) is inversely proportional to the wavelength, red light (longest in wavelength) is the lowest in energy. As wavelengths contract toward the blue end of the visible region of the electromagnetic spectrum, the frequencies and energies of colors steadily increase.

Like colors in the visible spectrum, other regions in the electromagnetic spectrum have distinct and important components. Radio waves, with wavelengths that range from hundreds of meters to less than a centimeter, transmit radio and television signals. Within the radio band, FM radio waves have a shorter wavelength and higher frequency than AM radio waves. Still higher frequency radio waves with wavelengths of a few centimeters can be utilized for **RADAR** imaging.

Microwaves range from approximately a foot in length to the thickness of a piece of paper. The atoms in food placed in a microwave oven become agitated (heated) by exposure to microwave radiation. Infrared radiation comprises the region of the electromagnetic spectrum where the wavelength of light is measured region from one millimeter (in wavelength) down to 400 nm. Infrared waves are discernible to humans as thermal radiation (heat). Just above the visible spectrum in terms of higher energy, higher frequency and shorter wavelengths is the ultraviolet region of the spectrum with light ranging in wavelength from 400 to 10 billionths of a meter. Ultraviolet radiation is a common cause of sunburn even when visible light is obscured or blocked by **clouds**. X rays are a highly energetic region of electromagnetic radiation with wavelengths ranging from about ten billionths of a meter to 10 trillionths of a meter. The ability of x rays to penetrate skin and other substances renders them useful in both medical and industrial radiography. Gamma rays, the most energetic form of electromagnetic radiation, are comprised of light with wavelengths of less than about ten trillionths of a meter and include waves with wavelengths smaller than the radius of an atomic nucleus (10^{15} m). Gamma rays are generated by nuclear reactions (e.g., radioactive decay, nuclear explosions, etc.).

Cosmic rays are not a part of the electromagnetic spectrum. Cosmic rays are not a form of electromagnetic radiation, but are actually high-energy charged particles with energies similar to, or higher than, observed gamma electromagnetic radiation energies.

ELECTRONS • *see* ATOMIC THEORY

ELEMENTS • *see* CHEMICAL ELEMENTS

ELLES, GERTRUDE (1872-1960)

English geologist

Throughout her life, Gertrude Elles made significant contributions to both the status of women in science, especially in the field of Earth sciences, and to the understanding of graptolites as zone **fossils** and their place within wider fossil communities.

Gertrude Lilian Elles was born in Wimbledon, Surrey near London, on October 8, 1872. At the age of 19, she attended Cambridge University studying the natural science Tripos, gaining a first class honors degree in 1895 and continuing on to become the first female to be awarded a Cambridge University Readership, 30 years later. She never married, but spent the majority of her life in Cambridge at Newnham College and was recognized as an excellent and enthusiastic teacher. Her name, however, was made not in the field of teaching, but in that of research. Elles' contribution to the study and classification of graptolites has not been surpassed to date. She spent 12 years compiling the Treatise on British Graptolites (with her colleague Ethel Wood) under the guidance of Charles Lapworth, (who named the **Ordovician Period**). Their names are inextricably linked with graptolite research. Her work on the genera of graptolites from North Wales and the Skiddaw Slates of the Lake District, England and from the Wenlock Shales of the Welsh borders eventually led to Elles' receiving the prestigious Lyell Fund from the Geological Society of London. She was not able to receive it in person as women were at that time (1900) barred from attending the meetings. She was one of the first scientists to look at not individual specimens of fossils, but at the concept of communities of organisms. In 1919, she became one of the first women to become a Fellow of the Geological Society of London and the same year she received the Murchison medal from the Society in recognition of her work. In 1922, she published a seminal work on the evolution and classification of graptolites from her long study of the group. However, her work also concentrated on **stratigraphy** and she published over 10 papers on lower Palaeozoic stratigraphy.

Among Elles' other accolades, she received the Medal of Member of the British Empire for her work with the British Red Cross in Britain during the First World War. She was an active worker with them for many years. She was also President of the British Association in 1923. Elles considered fieldwork the key to good **geology** and an understanding of paleontology and stratigraphy. Eventually her love of her homeland Scotland called her back permanently (she had always spent considerable time there fishing and researching metamorphic rocks), and Gertrude Elles died in Scotland in 1960 at the age of 88.

See also Fossil record; Fossils and fossilization

EMPEDOCLES OF ACRAGAS, (CA. 492 B.C.-CA. 432 B.C.)

Greek philosopher, poet, and politician

A philosopher, poet, politician, and visionary, Empedocles of Acragas developed radical new ideas about the nature of the universe. His philosophy of the four elements in the universe and the definition of matter as the various ratios of these elements foreshadowed later developments in **atomic theory** by philosophers such as Democritus of Abdera (c. 460–c. 370 B.C.).

Empedocles was born in Acragas, Sicily. His father, Meto, was wealthy, and his grandfather, also named Empedocles, was renowned for winning a horse race in the Olympia. Empedocles is believed to have travelled to Thourioi shortly after it was established approximately 444 B.C. Empedocles's keen intellect enabled him to combine talents in philosophy, natural history, poetry, and politics, and to achieve superstar status in his day. According to the Greek philosopher Aristotle (384–322 B.C.), Empedocles was the inventor of rhetoric, a talent Empedocles often utilized as a statesman. He became popular among his fellow citizens through his support of democracy.

Empedocles's scientific inquiries usually included mysticism. However, his philosophies contained early insight into basic laws of **physics**, including atomic theory. Although sometimes labeled a Pythagorean, Empedocles followed the Greek philosopher Parmenides (c. 515–c. 445 B.C.) in the belief that matter (or, "what is") is indestructible. Empedocles claimed that matter was the only principle of all things and that four elements in the universe—air, fire, earth, and water—made up all things according to various ratios of these elements. Empedocles further stated that two forces, which he called love and hate, or eros and strife, controlled how the four elements come together or move apart. In addition to creating a philosophy that closely resembles modern atomic theory, Empedocles also studied the nature of change in the universe. Empedocles asserted that the cyclical nature of the universe introduces the possibility of reincarnation because nothing that comes into being can be destroyed but only transformed. Empedocles later wrote a poetic treatise *On Nature* containing the ideas of **evolution**, the circulation of the blood, and **atmospheric pressure**. He stated that the **Moon** shone by reflected light and estimated that the Moon was one-third the distance from the earth to the **Sun**.

The object of admiration, Empedocles, according to Aristotle, was offered a kingship but refused to be considered king. Nevertheless, some scholars claim that Empedocles assumed royal status and went so far as to claim himself a deity. Viewed by some as a demi-god and by others as a charlatan, Empedocles made important contributions to the philosophy of science in his day. Galen (c. 130–c. 200), the physician to several Roman emperors, also credits Empedocles with founding the Italian school of medicine. In addition, Empedocles was an accomplished poet. However, little remains of his writings except for segments of his poems *On Nature* (*Peri Physeos*) and *Purifications* (*Katharmoi*). That Empedocles had a flair for self-promotion and public relations is evident in scholarly writings. Empedocles was reported to have leapt into the crater of the Mt. Etna **volcano** so he would have a death befitting a god. The English poet, Mathew Arnold, wrote a poem about the episode entitled *Empedocles on Etna*. Some scholars dispute the story of Empedocles' fiery death. According to the writings of Aristotle, Empedocles died at the age of 60.

ENERGY TRANSFORMATIONS

Energy is a state function that is best defined as the capacity to do work or to produce heat. There are many forms of energy (e.g., radiant energy, kinetic energy, potential energy, etc) each of which can be converted into other forms of energy. The fundamental law of thermodynamics states that the total energy of the universe is fixed and that energy can not be created or destroyed—only converted from one form to another.

Energy can be changed, or transformed, from one form into another. Energy transformation is also called energy conversion. The Système International d'Unités (SI) unit for energy is the joule (J), named after James Joule, who demonstrated that work can be converted into heat. The Joule is the fundamental unit of energy for both work and heat and is the work done by a force of one Newton acting through a distance of one meter. The joule is also equal to 1/4.184 of a calorie. Energy is often expressed as the calorie (cal), which is the amount of heat needed to raise the **temperature** of one gram of **water** by one degree Celsius at a pressure of one atmosphere. One calorie is equal to 4.184 joules. The Calorie (Cal; also called the kilocalorie) that is used to express the energy in food, is equal to 1,000 calories.

Kinetic energy is the energy of an object in motion and is related by the Newtonian formula $1/2mv^2$ (where m equals mass in Kg and v equals velocity in meters/second). An object in motion can cause another object to do work by colliding with it, causing it to move a particular distance. The colliding objects can be a hammer swinging down on a nail, or two atoms colliding in a chemical reaction. Examples of kinetic energy include mechanical energy (caused by motion of parts) and thermal energy (caused by the random motion of particles of matter). An object that has potential energy has energy by virtue of position and is related by the Newtonian equation $PE=mgh$ (where m equals mass in Kg, g the acceleration due to gravity—approximately 9.8 m/s^2 near Earth's surface—and h equals height in meters). At some point, that object had work performed on it, which resulted in energy storage. One example of performing work on an object to give it potential energy is the lifting of a body against the gravitational force of the Earth. As it is lifted, the body gains potential energy that is converted into kinetic energy as the body falls.

Another example of potential energy is water in an elevated tank. If water is allowed to fall on a wheel and the wheel turns, the turning wheel can be used to produce **electricity**. The water in the tank has gravitational potential energy. The potential energy of the water is transformed into mechanical energy of the wheel, that is then further transformed into electrical energy.

In 1845, Joule performed an experiment that demonstrated energy transformation both qualitatively and quantitatively. The experiment was not complicated—he placed a paddle wheel in a tank of water and measured the temperature of the water. He cranked the wheel in the water for a period of time, then read the temperature again. He found that the temperature of the water rose as he cranked the paddle wheel. Joule quantified this observation and discovered that an equal amount of energy was always required to raise the temperature of the water by one degree. He also discovered that it did not have to be mechanical energy; it could be energy in any form. He obtained the same results with electrical or magnetic energy as he did with mechanical energy. Joule's experiments showed that different forms of energy are equivalent and can be converted from one form to another.

Interestingly, as Joule expressed it, the energy required to increase one pound of water by one degree on the Fahrenheit scale is equal to the amount of energy obtained by a weight of 890 pounds after falling one foot in Earth's gravitational field.

These observations led to what is now called the "Law of conservation of energy." This law states that any time energy is transferred between two objects, or converted from one form into another, no energy is created and none is destroyed. The total amount of energy involved in the process remains the same.

Most chemical reactions involve transformations in energy. A chemical reaction is simply the process whereby bonds are broken between atoms and new ones are made.

The ultimate example of energy transformation is that of the radiant energy of the **Sun**. All of the energy on Earth originates from the Sun, energy left over from the formation of Earth (usually thermal energy caused by the gravitational collapse of matter), or energy derived from nuclear decay in Earth's interior.) The thermal energy in Earth's interior drives **plate tectonics** and, at the surface, the Sun's radiant energy is converted by plants into chemical energy through the process of photosynthesis. This chemical energy is stored in the form of sugars and starches. When these plants are eaten by animals (i.e., as part of the food chain), this chemical energy is either transformed into another form of chemical energy (fats or muscle) or used for mechanical or thermal energy. With regard to fossil **fuels**, the fuels used in the modern era derive from the transformations of **solar energy** over millions of years.

See also Earth (planet); Earth, interior structure; Earthquakes; K-T event; Landslide; Mass movement; Radioactivity

ENVIRONMENTAL POLLUTION

Scottish-American naturalist and Sierra Club founder, **John Muir** (1838–1914), wrote, "When we try to pick out anything by itself, we find it hitched to everything else in the Universe." Our rapidly growing, ever more industrialized human population exists within a carefully balanced global system of physical processes that circulates **chemical elements** through the solid earth, hydrosphere, atmosphere, and **biosphere**. From agricultural land and **water** management, to extraction and combustion of fossil **fuels**, to industrial and municipal disposal of waste products, modern human activity has overprinted natural Earth cycles with synthetic ones. In many cases, these man-made alterations to the natural environment negatively impact the very Earth systems that sustain human life. Contamination of the hydrosphere and atmosphere, depletion of radiation-shielding stratospheric **ozone**, and anthropogenic global **climate** change are examples of changes induced by human environmental pollution.

Accessible, uncontaminated water is essential to all human activities, and **water pollution** is a persistent environmental issue. Contamination of surface, ground, ocean, and atmospheric water occurs when chemical, radioactive, and organic waste is washed, spilled, or dumped into water reservoirs at point and non-point sources. Point sources of water pollution introduce concentrated waste products into **rivers**, aquifers, and **oceans** at focused entry points. Point sources such as oil spills, chemical leaks, and sewage discharges can often be easily corrected; the inflow of hazardous waste can be stopped, and the contaminated water reservoir can sometimes be cleansed. However, the immediate damage to ecosystems and water quality by highly concentrated chemicals at the spill site or pipe outlet may be irreversible, and cleanup is usually costly and difficult. The 1989 Exxon Valdez oil spill in Prince William Sound, Alaska was a dramatic example of a point source of marine water pollution.

Damaging materials also flow into streams and aquifers from diffuse, non-point sources like agricultural lands, logging tracts, mines, residential leach fields, and urban pavement. While non-point pollution is usually less concentrated, it is also more difficult to control, contain, and regulate. Furthermore, the environmental effects of non-point pollutants like fertilizers, pesticides, animal manure, and mining leachates often manifest themselves as systemic changes to aquatic environments that, in turn, reduce water quality. For example, addition of organic materials, fertilizers, and detergents to streams and **lakes** enhances the natural process of eutrophication, in which aquatic vegetation chokes a stream or lake, and eventually kills the reservoir's aquatic fauna. Even very low concentrations of toxic heavy **metals** like those found in leachates from mine tailings, or **lead** plumbing, can result in toxic contamination of fish and mammals in an aquatic ecosystem. Untreated sewage and agricultural **runoff** may introduce viral and bacterial pathogens that cause an array of human illnesses from typhoid to dysentery.

Groundwater pollution occurs when contaminants enter an **aquifer** from a point or non-point source in a recharge zone, contaminated surface water infiltrates, or buried tanks and landfills leak into the groundwater. Groundwater flow paths are complex, and the ultimate site of contamination is often difficult to predict. In karst aquifers, groundwater flows fairly rapidly through interconnected **limestone** dissolution cavities with little filtration of dissolved materials. Pollutants may thus be flushed from the groundwater in months or weeks, but contaminants often take unexpected paths through limestone aquifers, and eventually discharge, undiluted, at unexpected locations. In homogenous, porous aquifers, like the **sandstone** Ogalla aquifer in the south central United States, pollutants flow slowly from their points of entry, and are naturally filtered over time. However, it is difficult to flush contamination from a sandstone aquifer, and recharge with fresh water is extremely slow. Groundwater contamination is of particular concern for sitting buried landfills, **petroleum** tanks, and particularly nuclear waste repositories. Groundwater contamination by harmful radioactive waste buried at nuclear weapons laboratories in Hanford, Washington, and Oak Ridge, Tennessee has cast doubt on nuclear **waste disposal** schemes.

Though contamination is often introduced into the atmosphere at point sources like smokestacks and exhaust pipes, air pollution is usually diffuse because **atmospheric circulation** is unconfined. Sulfur dioxide emitted by coal-burning electrical generators disperses widely into the atmosphere before chemically combining with water vapor to form sulfuric acid. The resulting corrosive **acid rain** falls on widespread areas far downwind of the original point source. Nitrogen oxides released from automobile engines are a main component of the brown **smog** that blankets many cities. Nitrogen oxide and sulfur dioxide combine with other atmospheric chemicals in strong sunlight to form ozone, the component of smog that affects respiration and irritates humans' eyes. Ironically, ozone is harmful to humans in the lower atmosphere, but ozone in the outer atmosphere shields us from harmful, carcinogenic ultra-violet radiation. Another class of man-made chemicals, called chlorofluorocarbons (CFCs), has chemically destroyed the shielding ozone in the **stratosphere** over **Antarctica**, creating the "Ozone Hole." CFCs are common industrial chemicals used in air conditioners, aerosol spray cans, refrigerators, and foam packaging.

The dramatic decrease in air and water quality during the twentieth century has spurred the scientific community to better understand the types of environmental pollution described above, and to devise solutions that reduce contamination. Many governments have enacted legislation that encourages these solutions. In the United States, the Environmental Protection Agency's Clean Water Act of 1972, and Clean Air Act of 1990 strictly regulate industrial, agricultural and municipal sources of air and water pollution. Improved understanding of such complex processes as groundwater and atmospheric flow has led to safer methods of waste disposal, from properly-sited, lined landfills, to air filters on smoke stacks, to carburetors on automobiles. Countries that have enacted these relatively inexpensive measures now enjoy much cleaner air and water than existed in the 1970s. In 1987, the international community signed the Montreal Protocol that eventually bans production of CFCs. However, a handful of the thorniest environmental problems facing the Earth's human population have consequences we have yet to understand, let alone reverse. Solutions to the most threatening and highly-politicized environmental issues, including global climate change, overpopulation, and loss of biological diversity may require significant international socioeconomic changes.

See also Atmospheric pollution; Global warming; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ozone layer depletion

EOCENE EPOCH

The Eocene Epoch, second of the five epochs into which the **Tertiary Period** is divided, lasted from 54 to 38 million years ago. Mammals became the dominant land animals during this epoch.

The Eocene Epoch (meaning dawn of the recent period, from the Greek *eos*, dawn, and *koinos*, recent), like the other epochs of the Tertiary Period, was originally defined in 1833 by the English geologist **Charles Lyell** (1797–1875) on the basis of how many modern species are found among its **fossils**. The Eocene Epoch was defined by Lyell as that time where 1–5% of the species were modern (i.e., are still alive today). The Eocene Epoch's boundaries are therefore arbitrary, not set by mass extinctions or other clear-cut events.

For most of the Eocene Epoch, the global climate was warm and rainy. **Ice** caps were small or nonexistent. Early Eocene Epoch sea levels were low, creating land bridges between **Asia** and **North America** via the Bering Strait, North America and **Europe** via Greenland, and **Australia** and **Antarctica**. Late in the epoch Antarctica drifted south, opening a deep-water channel between it and Australia that caused a global cooling trend by allowing the formation of the circum-Antarctic current.

The Eocene Epoch saw the replacement of older mammalian orders by modern ones. Hoofed animals first appeared, including the famous Eohippus (dawn horse) and ancestral rhinoceroses and tapirs. Early bats, rabbits, beavers, rats, mice, carnivorous mammals, and whales also evolved during the Eocene Epoch. The earliest Eocene Epoch mammals were all small, but larger species, including the elephant-sized titanothere, evolved toward the end of the epoch.

Many flowering plants evolved in the Eocene Epoch. Especially important are the grasses, which had first appeared in the late **Cretaceous Period** but did not become diverse and ubiquitous until the Eocene Epoch. Abundant grass encouraged the **evolution** of early grazing animals, including Eohippus. Familiar tree species such as birch, cedar, chestnut, elm, and beech flourished during the Eocene Epoch; aquatic and insect life were much the same as today.

See also Archean; Cambrian Period; Carbon dating; Cenozoic Era; Dating methods; Devonian Period; Fossil record; Geologic time; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period;

Oligocene Epoch; Ordovician Period; Paleozoic Era; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period

EOLIAN PROCESSES

Eolian processes are processes of **relief** formation resulting from the action of **wind**. The term comes from the name of the Greek god of winds, Aeolus, and is sometimes referred to as Aeolian processes.

The effectiveness of Eolian processes depend on several factors: the average wind speed in a given **area**, the availability of transportable material, the factors hindering this transportation (such factors are mainly rich vegetation coverage on the surface and high moisture of **soil** and sediments). Eolian processes are inherent mostly in deserts and in areas with arid climates, but they occur also on beaches, glacial outwash valleys, snow surfaces, and in several other kinds of environment.

There are various modes of Eolian transport. **Creep** refers to a rolling and sliding transport. **Saltation** involves short hops ranging from centimeters to a meter. During reptation, numerous particles are displaced as splash close to the surface by impact bombardment of higher energy saltating grains. In suspension, short (up to hundreds of meters) and long term (up to thousands of kilometers) of fine-grained silts and **clay** sized sediment are transported.

Spatial and temporal variations in the Eolian transport processes and in the conditions of their development give rise to various erosional and depositional **landforms**. Ventifacts, rocks abraded and fluted by constant impact of **sand** grains, are an example of erosional landforms. Yardangs are abrasion ridges aligned in the direction of transporting winds. Other erosional landforms include **desert** pavement and deflation lag deposits. Depositional landforms are massive fine-grained deposits of windblown loess (silt), giving rise to sand sheets, ripples, and **dunes**. **Superposition** of forms of different orders is characteristic of Eeolian landforms.

Eolian processes are of interest to scientists of applied **geology**. For example, they can influence the formation of gold placers in several regions.

See also Dune fields; Erosion

EON • *see* GEOLOGIC TIME

EPOCH • *see* GEOLOGIC TIME

EQUATOR • *see* LATITUDE AND LONGITUDE

EQUINOX • *see* LATITUDE AND LONGITUDE

ERA • *see* GEOLOGIC TIME

ERATOSTHENES OF CYRENE

(276 B.C.-194 B.C.)

Greek astronomer

Using elegant mathematical reasoning and limited empirical measurement, in approximately 240 B.C., Eratosthenes of Cyrene (in current-day Libya) made an accurate measurement of the circumference of Earth. In addition to providing evidence of scientific empiricism in the ancient world, this and other contributions to geodesy (the study of the shape and size of the earth) spurred subsequent exploration and expansion. Ironically, centuries later the Greek mathematician and astronomer Claudius Ptolemy's erroneous rejection of Eratosthenes' mathematical calculations, along with other mathematical errors, resulted in the mathematical estimation of a smaller Earth that, however erroneous, made extended seagoing journeys and exploration seem more tactically achievable.

Eratosthenes served as the third librarian at the Great Library in Alexandria. Serving under **Ptolemy** III and tutor to Ptolemy IV, the head librarian post was of considerable importance because the library was the central seat of learning and study in the ancient world. Ships coming into the port of Alexandria, for example, had their written documents copied for inclusion in the library and, over the years, the library's collection grew to encompass hundreds of thousands of papyri and vellum scrolls containing much of the intellectual wealth of the ancient world.

In addition to managing the collection, reading, and transcription of documents, Eratosthenes' own scholarly work concentrated on the study of the mathematics related to Platonic philosophy. Although Eratosthenes actual writings and calculations have not survived, it is known from the writings of other Greek scholars that Eratosthenes' writings and work treated the fundamental concepts and definitions of arithmetic and geometry. Eratosthenes' work with prime numbers, for example, resulted in a prime number sieve still used in modern number theory. Eratosthenes' also contributed to the advancement of scientific knowledge and reasoning, including the compilation of a large catalogue of stars and the preparation of influential chronologies, calendars and maps. So diverse were Eratosthenes' scholarly abilities that he was apparently referred to by his contemporaries as "Beta," a reference to the fact that although Eratosthenes was well-grounded in many scholarly disciplines, he was seemingly second-best in all.

Eratosthenes is, however, best known for his accurate and ingenious calculation of the circumference of the earth. Although Eratosthenes' own notes regarding the methodology of calculation are lost to modern historians, there are tantalizing references to the calculations in the works of Strabo and other scholars. There are extensive references to Eratosthenes' work in Pappus's Collection, an A.D. third century compilation and summary of work in mathematics, **physics**, **astronomy**, and geography. Beyond making an accurate estimate of the earth's circumference, based on observations of shifts in the zenith position of the **Sun**, Eratosthenes also made very accurate measurements of the tilt of the earth's axis.

Apparently inspired by observations contained in the scrolls he reviewed as librarian, Eratosthenes noticed subtle differences in accounts of shadows cast by the midday summer sun. In particular, Eratosthenes read of an observation made near Syene (near modern Aswan, Egypt) that at noon on the summer solstice, the Sun shone directly on the bottom of a deep well and that upright pillars were observed to cast no shadow. In contrast, Eratosthenes noticed that in Alexandria on the same day the noon Sun cast a shadow on a stick thrust into the ground and upon pillars.

Based upon his studies of astronomy and geometry, Eratosthenes assumed that the Sun was at such a great distance that it could be assumed that its rays were essentially parallel by the time they reached the Earth. Although the calculated distances of the Sun and the **Moon**, supported by measurements and estimates made during lunar eclipses, were far too low, the assumptions made by Eratosthenes proved essentially correct. Utilizing such an assumption regarding the parallel incidence of light rays, it remained to determine the angular variance between the shadows cast at Syene and Alexandria at the same time of day. In addition, Eratosthenes needed to calculate the distance between Syene and Alexandria.

Given modern methodologies, it seems intuitive that Eratosthenes would set out to establish the values of angle and distance needed to complete his calculations. In the ancient world, however, Eratosthenes' empiricism, reflected in his actual collection of data, reflected a significant break from a scholarly tradition that relied upon a more philosophical or mathematical approach to problems. Moreover, Eratosthenes' solution relied upon a world-view, especially reflecting the spheroid shape of the world, that itself was subject to philosophical debate.

Eratosthenes ultimately determined the angular difference between the shadows at Syene and Alexandria to be about seven degrees. Regardless of how he obtained the distance to Syene (some legends hold that he paid a messenger runner to pace it off), Eratosthenes reasoned that the ratio of the angular difference in the shadows to the number of degrees in a circle (360 degrees) must equal the ratio of the distance (about 500 mi, or 805 km) to the circumference of the earth. The resulting estimate, about 25,000 mi (40,200 km), is astonishingly accurate.

In making his calculations, Eratosthenes measured distance in units termed stadia. Although the exact value of the stadia is not known, modern estimates place it in the range of 525 ft (160 m). Depending on the exact value of the stadia, Eratosthenes' estimate varied only a few percent from the modern value of 24,902 mi (40,075 km) at the equator. It is necessary to specify that this is the circumference at the equator because the earth is actually an oblate sphere (a slightly compressed sphere with a bulge in the middle) where the circumference at the equator is greater than the distance of a great circle passing through the poles.

Although Eratosthenes' calculations were disputed in his own time, they allowed the development of maps and globes that remained among the most accurate produced for more than a thousand years. The interest in geography and geodesy emboldened regional seafaring exploration using only the most primitive navigational instruments. Moreover, Eratosthenes' calculations fostered the persistence of belief in the sphericity of the earth that ultimately allowed for the development of the concept of antipodes and an early theory of climatic zones dependent on distance from the earth's equator. Eratosthenes' work, encapsulating many of his theories, was reported to have been the first to use the term geography to describe the study of Earth.

Erosive forces are pushing this cliff further back, endangering the fence and gatehouse, and eventually the main house itself. © *Vince Streano/Corbis. Reproduced by permission.*

ERGS • *see* DUNE FIELDS

EROSION

Erosion is the reduction or breakdown of **landforms** exposed to the forces of **weathering** (disintegration and decomposition). Weathering and subsequent erosion may be caused by both chemical or mechanical forces. Mechanical weathering agents include **wind**, **water**, and **ice**. Chemical weathering leading to erosion results from bio-organic breakdown, hydration, hydrolysis, and oxidation processes. The process of transportation describes the movements of eroded materials.

Erosion requires a transport mechanism (e.g., **gravity**, wind, water, or ice). Wind, water, and ice are also agents of erosion that cause the physical breakdown of **rock** and landforms.

A special form of erosion, **mass wasting**, describes the transport of material downslope under the influence of gravity. Landslides are a common example of mass wasting.

Erosion processes can also cause indirect landform alteration by breaking down overburden of rock and precipitating a pressure release that can crack and shift rock layers. The cracking process results in peels, **exfoliation**, or spalling. For example, the erosion of overburden can expose batholiths and these exposed formations can form exfoliation domes.

Organic materials can frequently contribute to erosion by pressure that results in structural cracking or in the formation of acidic compounds that **weather** rock.

Rapid **temperature** changes or large diurnal temperature changes (the difference between the highest daytime temperature and the coolest nighttime temperature) can accelerate erosional exfoliation, jointing, and ice wedging.

See also Acid rain; Catastrophic mass movements; Depositional environments; Dunes; Eolian processes; Faults and fractures; Freezing and melting; Glacial landforms; Glaciation; Hydrothermal processes; Ice heaving and ice wedging; Impact crater; Landforms; Landscape evolution; Leaching; Oxidation-reduction reaction; Precipitation; Rapids and waterfalls; Rate factors in geologic processes; Rock; Rockfall; Salt wedging; Seawalls and beach erosion; Soil and soil horizons; Talus pile or talus slope.

ESCAPE VELOCITY • *see* GRAVITY AND THE GRAVITATIONAL FIELD

ESKERS • *see* GLACIAL LANDFORMS

ESTUARY

Estuaries are unique and complex environments located between **oceans** and river mouths. As **freshwater** flows into the sea from land, it dilutes the salty **water** in a small **area** around the shore. This relatively small space is the site of sediment build-up resulting from fluvial (stream or river) **erosion** along the riverbanks. The organic sediments and brackish (slightly salty, but undrinkable) water make a unique environment that supports a diverse community of plants and animals. The sediments themselves also form characteristic types of deposits and bed forms (the appearance of the horizontal layers of **sand**) that are easily seen in cross-section.

It is well known that **rivers** often carry tremendous amounts of sediment which, when emptied into the oceans, construct distinctive patterns in the underlying sediments. In an estuary, the deposition of sediments is greatly influenced by tidal currents and ocean waves. Even **climate** is a factor in how the sands and muds settle into distinct patterns. During seasonal storms, erosion is increased and the waters become heavily laden with a wide variety of sediments. Unlike deltas, in which the finer sediments are often carried far out to sea, the estuary is bordered on the deeper ocean side by heavy sands while clays and muds are dropped at river mouths. As tidal forces work the sediments by tumbling and rolling them, the lighter and finer particles are left near the river mouth. The build-up of coarse-grained (larger particle size) sands at the estuary edge often makes a barrier at the outer edge of the estuary that contains the bulk of the fine sediment and diluted water. The sediment structures in these ridges are defined as longitudinal or oblique bars. The structures in the upper reaches of the estuary are described as asymmetric and longitudinal bars become point bars similar to those observed in rivers. A dendritic (tree-shaped) pattern of channels occurs in these finer, flat lying sediments.

The greatest force at work shaping and changing the estuary comes from moving water. Daily tidal fluctuation brings saltier water into the estuary and pushes medium-grained sands into the main body of the tidal flats. On the ocean side of the estuary, the sand bars are penetrated by channels through which the flow of water into and out of the estuary is restrained. These containment structures close the general water and sediment circulation paths around the main body of the estuary. Water and sediment flow is greatly restricted and additional build-up of medium and fine-grained sediments occurs. Water is forced to leave the estuary by these well-defined channels.

The tidal or exit channels of the estuary can be dangerous places for some life forms. As low tide occurs, the ebb of general sea level reverses the oceanic flow into the estuary. Water laden sediments release their burden and contribute to the general volume of water leaving the flats. The force of water exiting through the channels becomes great. The velocity of the water can reach dangerously high levels. In well-established estuaries, large animals can be swept to sea. However, for many marine animals this is a benefit.

The estuaries are safe places for many creatures such as crabs and other crustaceans to lay their eggs. The hatched larvae live in the estuary until they are ready to join the zooplankton community of the larger sea. The swift release of water from the tidal flats helps the floating larvae to jet far out into the ocean where they will spend the next phase of their lives. If not for the tidal currents, the larvae would have to live dangerously exposed to shore birds and other marine carnivores. The estuarine water channels help them grow and gain a slight advantage for survival that would not be found in typical shore lines.

When high tide returns, the encroaching water brings **oxygen** to the anaerobic (without oxygen) sediments. The water also brings marine organic food for mud dwelling inhabitants. The sediments are refreshed with salt water and another cycle of replenishment occurs. During stormy **seasons**, this effect can be exaggerated and actually quite harmful to inhabitants as sediments are churned and redeposited. However, this continuous recycling of sediments and resources keeps the estuary healthy and flourishing.

Because the water plays such a physical and active role near the outer borders of the estuary, the inner regions of the estuary are more protected. By containing the general flow of water to the channels, the finer sediments, such as silt and **clay**, are left relatively undisturbed near the river mouths. They build up into areas of fine muds and contribute to the distinctive tidal flats. Organic debris is carried along by the rivers as they carve through valleys and plains of the terrestrial environment. This lightweight material comes to rest in the tidal flat as the velocity of the water is drastically reduced in the tidal flats. The decay and spreading of organic material throughout the flats makes them rich in nutrients. Subsequently, clams and other burrowing animals thrive in the rich sediments of the upper estuary. In turn, birds are lured to this feast where they are able to rear young on the nearby shore. These life forms are relatively protected because the muds make it difficult for heavier predators to walk out into the estuary with any stealth. There are even places where the muds act as a sort of quicksand and can be very dangerous.

Estuaries are fragile environments that are becoming increasingly threatened. They are being geologically altered as sediments are trapped upstream by dams. Diversion of water and sediments by agriculture is also reducing flow to the estuary. As a direct result, the life forms that rely on the dynamics of the estuary are decreasing in numbers. Many people are realizing the importance of estuarine environments and the important role they play in both marine and terrestrial ecosystems.

See also Oceanography; Sedimentation; Tides

EUROPE

The continent of Europe is a landmass bounded on the east by the Ural Mountains, on the south by the Mediterranean Sea, and on the north and west by the Arctic and Atlantic **Oceans**. Numerous islands around this landmass are considered a part of Europe. Europe is also the westernmost part of the Eurasian supercontinent (several continental masses joined together). Europe is a collection of different kinds of geologic regions located side by side. Europe holds a unique place among the continents; much of it is new, in geologic terms.

Plate tectonics is the main force of nature responsible for the geologic history of Europe. European geologic history, like that of all the continents, involves the formation of features as a result of plate tectonics.

When the edge of a plate of Earth's **lithosphere** runs over another plate, forcing the lower plate deep into the elastic interior, a long, curved chain of volcanic mountains usually erupts on the forward-moving edge of the upper plate. When this border between two plates forms in an ocean, the volcanic mountains constitute a string of islands (or archipelago). This is called an island arc. Italy's Appenine Mountains originally formed as an island arc, then later became connected into a single peninsula.

A continental arc is exactly like an island arc except that the volcanos erupt on a continent, instead of in the middle of an ocean. The chemical composition of the erupted **rock** is changed, because old continental rocks at the bottom of the lithosphere have melted and mixed with the **magma**. A clear-cut example of this kind of mountain chain no longer exists in Europe, but ancient continental arcs once played an important part in Europe's geologic past. Sicily's Mt. Aetna and Mt. Vesuvius on the Bay of Naples are good examples of the type of **volcano** that commonly make up a continental arc.

A suture describes the place where two parts of a surgery patient's tissue are sewed or rejoined; it also describes the belts of mountains that form when two continents are shoved into each other, over tens of millions of years, to become one. The Alps and other ranges in southern Europe stand tall because of a continental collision between Europe and **Africa**. The Alps, and other European ranges, are the forerunners of what may be a fully developed suture uniting Europe and Africa. This suture would be a tall mountain range that stretches continuously from Iberia to easternmost Europe.

The collision of Africa with Europe is a continuous process that stretches tens of millions of years into the past and into the future. All the generations of humanity together have seen only a tiny increment of the continental movement in this collision. However, throughout history, people have felt the collision profoundly, in earthquakes and volcanos, with all the calamities that attend them.

Sometimes a continent is torn in pieces by forces moving in opposite directions beneath it. On the surface, this tearing at first makes a deep valley, which experiences both volcanic and **earthquake** activity. Eventually the valley becomes wide and deep enough that its floor drops below sea level, and ocean **water** moves in. This process, called **rifting**, is the way ocean basins are born on Earth; the valley that makes a place for the ocean is called a rift valley. Pieces of lithosphere, rifted away from Africa and elsewhere, have journeyed across the Earth's surface and joined with the edge of Europe. These pieces of lithosphere lie under southern England, Germany, France, and Greece, among other places.

When a continent-sized "layer cake" of rock is pushed, the upper layers move more readily than the lower layers. The upper layers of rock are heavy but easier to move than those beneath it (much like a full filing cabinet is heavy but, when pushed, moves more easily than the floor beneath it). Between near surface rocks and the deeper, more ancient crustal rocks, a flat-lying fault forms, also called a detachment fault. This horizontal crack, called a thrust fault, contains fluid (water, mostly). The same hydraulic force that makes hydraulic machines lift huge weights functions in this crack as well. The fluid is so nearly incompressible that a sizeable piece of a continent can slide on it when pushed. The fault block floats on fluid pressure between the upper and lower sections of the lithosphere like a fully loaded tractor trailer gliding effortlessly along a rain-slicked road. The mountains that are heaved up where the thrust fault reaches the surface are one kind of fault block mountains. Both the Jura Mountains and the Carpathians are fault block mountains.

The white cliffs of Dover, composed almost entirely of chalk, are a familiar landmark of the British Isles. ***JLM Visuals. Reproduced by permission.***

Europe was not formed in one piece, or at one time. Various parts of it were formed all over the ancient world, over a period of four billion years, and were slowly brought together and assembled into one continent by the processes of plate tectonics. What is now called Europe began to form more than 3 billion years ago, during the **Archean** Eon.

Most geologists feel that prior to and during the creation of the oldest parts of Europe, Earth only superficially resembled the planet we live on today. Active volcanos and rifts abounded. The planet had cooled enough to have a solid **crust** and oceans of liquid water. The crust may have included hundreds of small tectonic plates, moving perhaps ten times faster than plates move today. These small plates, carrying what are now the earth's most ancient crustal rocks, moved across the surface of a frantic crazy-quilt planet. Whatever it truly was like, the oldest regions in Europe were formed in this remote world. These regions are in Finland, Norway (Lofoten Islands), Scotland, Russia, and Bulgaria.

The piece of Europe that has been in its present form for the longest time is the lithospheric crust underneath Scandinavia, the Baltic states, and parts of Russia, Belarus, and Ukraine. This region moved around independently for a long time, and is referred to as Baltica. It is the continental core, or **craton**, to which other parts were attached to form Europe.

At the opening of the **Mesozoic Era**, 245 million years ago, a sizeable part of western and southern Europe was squeezed up into the Central Pangean mountain system that sutured Laurasia and Gondwana together. Pangea was the huge landmass from which all continents drifted; Laurasia and Gondwana were the two **supercontinents** that Pangea separated into about 200 million years ago. Europe was almost completely landlocked, its southern regions part of a mountain chain that stretched from Kazakhstan to the west coast of **North America**.

The birth of a new ocean basin, the Atlantic, signaled the end of Pangea. The Central Pangean Mountains, after tens of millions of years, had worn down to sea level and below. A new ocean basin, not the Mediterranean, but rather the Ligurean Ocean, began to open up between Africa and Europe. This formed a seaway between the modern North Atlantic and the Neo-Tethys Ocean (which no longer exists). Sea water began to leave deposits where high mountains had stood, and a layer cake of sediment—laid down on the shallow sea bottom—began to accumulate throughout Europe.

Beginning at the close of the Mesozoic Era (66 million years ago), and continuing through the **Cenozoic Era** to the present day, a complex **orogeny** (mountain building) has taken place in Europe. The ocean basin of Tethys was entirely destroyed, or if remnants still exist, they are indistinguishable from the ocean crust of the Mediterranean Sea. Africa has shifted from west of Europe (and up against the United States' East Coast) to directly south of Europe, and their respective tectonic plates are now colliding.

As in the collision that made the Variscan mountain belt, a couple of dozen little blocks are being pushed sideways into southern Europe. The tectonic arrangement can be compared with a traffic jam in Rome or Paris, where numerous moving objects attempt to wedge into a **space** in which they cannot all fit.

When sea level fell below the level of the Straits of Gibraltar around six million years ago, the western seawater passage from the Atlantic Ocean to the Mediterranean Sea closed, and water ceased to flow through this passage. At about the same time, northward-moving Arabia closed the eastern ocean passage out of the Mediterranean Sea and the completely landlocked ocean basin began to dry up. Not once, but perhaps as many as 30 times, all the water in the ancestral Mediterranean, Black, and Caspian **Seas** completely evaporated, leaving a thick crust of crystallized sea **minerals** such as **gypsum**, sylvite, and halite (salt). It must have been a lifeless place, filled with dense, hot air like modern below-sea-level deserts such as Death Valley and the coast of the Dead Sea. The **rivers** of Europe, **Asia**, and Africa carved deep valleys in their respective continental slopes as they dropped down to disappear into the burning salt wasteland.

Many times, too, the entire basin flooded with water. A rise in global sea level would lift water from the Atlantic Ocean over the barrier mountains at Gibraltar. Then the waters of the Atlantic Ocean would cascade 2.4 mi (4 km) down the mountainside into the western Mediterranean basin. From Gibraltar to central Asia, the bone-dry basin filled catastrophically in a geological instant—a few hundred years. This "instant ocean" laid deep-sea sediment directly on top of the layers of salt. The widespread extent and repetition of this series of salt and deep-sea sediment layers is the basis for the theory of numerous catastrophic **floods** in the Mediterranean basin.

For reasons not yet fully understood, Earth periodically experiences episodes of planet-wide climatic cooling, the most recent of which is known as the **Pleistocene Epoch**. Large areas of the land and seas become covered with **ice** sheets thousands of feet thick that remain unmelted for thousands or hundreds of thousands of years. Since the end of the last ice age about 8,000–12,000 years ago, only Greenland and **Antarctica** remain covered with continent-sized **glaciers**. But during the last two million years, Europe's northern regions and its mountain ranges were ground and polished by masses of water frozen into miles-thick continental glaciers.

Ice in glaciers is not frozen in the sense of being motionless. It is in constant motion—imperceptibly slow, but irresistible. Glaciers subject the earth materials beneath them to the most intense kind of scraping and scouring. An alpine glacier has the power to tear **bedrock** apart and move the shattered pieces miles away. These are the forces that shaped the sharp mountain peaks and u-shaped mountain valleys of modern Europe. Many European mountain ranges bear obvious scars from alpine **glaciation**, and the flat areas of the continent show the features of a formerly glaciated plain.

Humans have lived in Europe for much of the Pleistocene Epoch and the entire **Holocene Epoch** (beginning at the end of the last ice age, about 10,000 years ago). During the past few thousand years, humans have been significantly altering the European landscape. Wetlands across Europe have been drained for agricultural use from the Bronze Age onward. The Netherlands is famous for its polders, below-sea-level lands made by holding back the sea with dikes. Entire volcanoes (cinder cones) have been excavated to produce frost-resistant road fill.

The northwest fringe of Europe is made up of the two very old islands, Great Britain and Ireland, and numerous smaller islands associated with them. Geologically, these islands are a part of the European continent, although culturally separate from it. Unlike many islands of comparable size, the British Isles do not result from a single group of related tectonic events. They are as complex as continents themselves, which in the last two centuries has provided plenty of subject matter for the new science of **geology**.

Scotland and Ireland are each made of three or four slices of continental crust. These slices came together around 400 million years ago like a deck of cards being put back together after shuffling.

The Iberian Peninsula, occupied today by Portugal and Spain, is one of the pieces of lithosphere that was welded to Europe during the Variscan mountain-building event. Like Britain, it is an unusual "micro-continent" with a complex geologic history.

Since the **Paleozoic Era**, southern Europe has continued to acquire a jumbled mass of continental fragments from Africa. Even today, the rocks of Europe from the Carpathian Mountains southwestward to the Adriatic and Italy are made up of "tectonic driftwood," and are not resting on the type of solid, crystalline basement that underlies Scandinavia and Ukraine.

Since the late Mesozoic Era, the widening Atlantic Ocean has been pushing Africa counterclockwise. All the blocks of lithosphere between Africa and Europe, including parts of the Mediterranean seafloor, will in all likelihood eventually become a part of Europe.

The Alps resulted from Europe's southern border being pushed by the northern edge of Africa. In Central Europe, freshly-made **sedimentary rocks** of early Mesozoic age, along with the older, metamorphosed, Variscan rocks below, were pushed into the continent until they had no other way to go but up. Following the path of least resistance, these rocks were shaped by powerful forces into complex **folds** called nappes, which means tablecloth in French. The highly deformed rocks in these mountains were later carved into jagged peaks by glaciers during the Pleistocene Epoch.

The Jura Mountains, the Carpathians, and the Transylvanian Alps are made of stacks of flat-lying sedimentary rock layers. These mountain ranges were thrust forward in giant sheets out in front of the rising Alps.

A complex story of tectonic movement is recorded in the sea-floor rocks of the western Mediterranean. Corsica, Sardinia, Iberia, and two pieces of Africa called the "Kabylies"—formerly parts of Europe—moved in various directions at various speeds throughout the Cenozoic Era.

On the western Mediterranean floor, new oceanic lithosphere was created. A **subduction zone** formed as an oceanic plate to the east sank below the western Mediterranean floor. The magma generated by this event gave rise to the Appenine Mountains, which formed as an island arc on the eastern edge of the western Mediterranean oceanic plate. The Appenines began to rotate counterclockwise into their present position. The Tyrrhenian Sea formed as the crust stretched behind this forward-moving island arc. In the Balkans, blocks of lithosphere have piled into each other over tens of millions of years.

The Dinarides and Hellenides, mountains that run down the east coast of the Adriatic Sea, form the scar left after an old ocean basin closed. The compressed and deformed rocks in these mountain ranges contain pieces of ocean floor. Just east of these seacoast mountains is a clearly-recognized plate boundary, where the European and African plates meet. The boundary runs from the Pannonian Basin (in Hungary, Romania, and Yugoslavia), cuts the territory of the former Yugoslavia in half, and winds up in Greece's Attica, near Athens.

Further inland, the Pannonian Basin results from the lithosphere being stretched as the Carpathian Mountains move eastward and northward.

The Aegean Sea seems to have formed as continental crust has been stretched in an east-west direction. It is a submerged basin-and-range province, such as in the western United States. The Pelagonian Massif, a body of igneous and **metamorphic rock** that lies under Attica, Euboea, and Mount Olympus, forms part of the Aegean sea floor. The Rhodopian Massif, in northern Greece, Bulgaria, and Macedonia, also extends beneath the Aegean Sea. Faults divide the ridges from the troughs that lie between them. The faults indicate that the troughs have dropped into the crust between the high ridges.

The Balkan Range in Bulgaria is thought to mark the crumpled edge of the European craton—the Proterozoic-age rocks extending north into Russia.

Europe is also host to isolated volcanoes related to structural troughs within the continent. The Rhine River flows in a trough known as the Rhine Graben. Geologists believe the Rhine once flowed southward to join the Rhone River in France, but was diverted by upwarping of the crust around the Vogelsberg Volcano. The Rhine then changed its course, flowing out to meet England's Thames River in the low-sea-level Ice Age.

Europe continues to change today. From the Atlantic coast of Iberia to the Caucasus, Europe's southern border is geologically active, and will remain so effectively forever, from a human frame of reference. Africa, Arabia, and the Iranian Plateau all continue to move northward, which will insure continued mountain-building in southern Europe.

Geologists are concerned about volcanic hazards, particularly under the Bay of Naples and in the Caucasus. In historic times, in the Aegean Sea and at Pompeii, Herculaneum, and Lisbon, entire cities have been devastated or destroyed by volcanoes, earthquakes, and seismic sea waves. These larger-scale natural disasters can and will continue to happen in Europe on an unpredictable schedule with predictable results.

See also Continental drift theory; Earth (planet); Historical geology

EVAPORATION

Evaporation is a geologic process that concentrates the ion solute residues in the ocean basins. At a fundamental level, evaporation is the transition of the molecule of a liquid from the liquid state to the gaseous state by diffusion from the surface of the liquid.

Driven by **solar energy**, the only significant loss of **water** from the ocean basin occurs via evaporation. As the ocean surface and atmospheric interface is small compared to the total volume of the ocean, estimates of the time a particular molecule remains in the liquid phase range in the order of thousands to tens of thousands of years before once again entering the atmosphere as part of the **hydrologic cycle**.

Because solutes (e.g., dissolved salts) from **weathering** and **erosion** are not as volatile (i.e., as easy to move into the gas or vapor phase as the water molecules, evaporation plays a significant role in the formation of many geologic features (e.g., Great Salt Lake, Dead Sea, etc.).

Evaporation is usually also responsible for the majority of the loss of water from **precipitation** and results in a high cycling of water molecules during the hydrologic cycle.

Evaporation may be driven by solar energy or be a directed process used to concentrate an aqueous solution of nonvolatile solutes and a volatile solvent. In evaporation, a portion of the solvent is vaporized or boiled away, leaving a thick liquid or solid precipitate as the final product. The vapor is condensed to recover the solvent or it can simply be discarded. A typical example is the evaporation of sea water to produce salt.

Evaporation may also be used as a method to produce a liquid or gaseous product obtained from the condensed vapor. For instance, in desalinization processes, sea water is vaporized and condensed in a water-cooled heat exchanger and forms the fresh water product.

Although evaporation can be driven by the random motion of molecules near the liquid-gas interface, the addition of heat to a system speeds the evaporative process.

See also Caliche; Condensation; Drainage calculations and engineering; Leaching; Oceans and seas; Phase state changes; Runoff

EVOLUTION

Evolution is the gradual, cumulative change over time of the characteristics of groups of organisms in a heritable manner. Eventually, these minute changes add up to produce an individual that is markedly different from its distant ancestors, but almost indistinguishable from its most immediate ancestors. These changes are brought about by the organism's genetic response to the environment, and, over the entire course of history, evolution has given rise to all different forms of life on Earth.

Evolution does not occur rapidly on the individual unit of life; changes are too small and slow to be effective at the individual level. In fact, evolution is more efficient at the pop-

The Bonneville Salt Flats in Utah were at one time covered by a sea of salt water. Evaporation removed the water, leaving the salt behind. © *Buddy Mays/Corbis. Reproduced by permission.*

ulation level among groups of organisms that are capable of successfully breeding with each other. With organisms that do not breed with other individuals, the rate of evolutionary change is slower than it is among outbreeding organisms.

Evolution leads to increasing complexity and, eventually, to the production of new species, which survive or become extinct depending upon their reaction to the environment and its continuing changes. Evidence for evolution comes from the **fossil record**, genetics, and comparative studies.

The mechanism behind evolution is natural selection. Small, individual changes that arise by chance can confer an advantage to those possessing them; this group then has better success at breeding, and successful genes are consequently spread further throughout the population. The theory of evolution is now widely accepted, but when it was first put forward in the nineteenth century by English naturalist Charles Darwin there was much opposition, particularly from religious quarters. Opponents to the theory of evolution often argue for special creation, which states that each type of species was created in the form in which it currently exists, and that no two species are related, by descent, to any other. Most scientists now accept the theory of evolution, as the concept of evolution fits available evidence. There exist some gaps in scientific knowledge of evolution, such as the discovery of the common ancestor for both apes and humans, often referred to as the missing link, but, with time, these knowledge gaps have become smaller.

Evolution does not proceed at a constant rate. At times, a gradual change occurs that allows for a good reconstruction of the process from the fossil record. This is known as phyletic gradualism. The other method of evolution, which can leave gaps in the fossil record is the quicker and more explosive form, called punctuated equilibrium.

See also Cosmology; Evolution, evidence of; Evolutionary mechanisms; Fossils and fossilization

EVOLUTION, EVIDENCE OF

Evidence of **evolution** can be observed in a number of different ways, including distribution of **fossils** of species both geographically and through **geologic time**. Evolution is a major scientific theory. As such, it has a tremendous amount of supporting evidence and no clearly contradicting evidence. If new evidence appears to refute it, then a new theory must be formulated. Any evidence requiring a totally new theory, however, would have to be staggering in its scope and strength. The new evidence that has been forthcoming in recent scientific studies supports the theory of evolution and merely fine tunes scientific understanding of the mechanisms involved.

A clear and strong argument in favor of evolutionary theory is found in the **fossil record**. Paleontology (the study of fossils) provides an unarguable record that many species no longer exist. By such techniques as **carbon dating** and studying the placement of fossils within the ground, an age can be given for fossils. By placing fossils together based on their ages, a gradual change in form can be surmised which can be followed and extrapolated to the species that exists today. Although the fossil record is incomplete, and many intermediate species are missing, the weight of evidence from those that do exist favors the theories of evolution and natural selection.

Extremely strong evidence supporting evolutionary theory is found in the strata of fossils. No fossils more ancient than those found in underlying layers have ever been found. This **correlation** of the geologic record with the biological evolutionary record is profound.

English naturalist Charles Darwin (1809–1882) formulated the theory of organic evolution through natural selection in his groundbreaking publication *The Origin of Species by Means of Natural Selection*, published in 1859. One of the first pieces of evidence that started the young scientist thinking along evolutionary lines was given to him on his journeys aboard the H.M.S. *Beagle*. Darwin made extensive collections of plants and animals that he came across wherever the ship stopped, and soon he started to notice patterns within the organisms he studied.

There were similarities between organisms collected from widely differing areas. As well as the similarities, there were also striking differences. For example, mammals are present on all of the major landmasses, but Darwin did not find the same mammals even in similar habitats. One explanation of this is that in the past when the landmasses were joined, mammals spread over all of the available land. Subsequently this land moved apart, and the animals became isolated. As time passed, random variation within the populations was acted upon by natural selection. This process is known as adaptive radiation—from the same basic stock, many different forms have evolved. Each environment is slightly different, and slightly different forms are better suited to survive there. An example of this, which is seen at a formative stage, is the case of the finches on the Galápagos Islands. All of the Galápagos finches bear similarities to the mainland finches, but each species has evolved to fill a particular **niche**, which is not already filled by an animal on the islands even though there are species filling these ecological openings on the mainland.

If it is true that widely separated groups of organisms have ancestors in common, then logic dictates that they would have certain basic structures in common as well. The more structures they have in common then the more closely related they must be. The study of evolutionary relationships based on commonalties and structural differences is termed comparative anatomy. What scientists look for are structures that may serve entirely different functions but are basically similar. Such homologous structures suggest a common ancestor. A classic example of this is the pentadactyl limb, which in suitably modified forms can be seen in all mammals. A greater modified version of this can also be seen amongst birds. This limb has been used by different groups for slightly different purposes and so provides an example of divergent evolution.

These evolutionary relationships are reflected in taxonomy. Taxonomy is an artificial, hierarchical system showing relationships between species. Each level progressed within the taxonomic system denotes a greater degree of relatedness for the organism in that group to the level above.

In embryology, the developing fetus is studied, and similarities with other organisms are observed. This adds evidence to a past recent common ancestor. It is not, however, true that a developing organism replays its evolutionary stages as an embryo; there are some similarities with the more conserved regions, but embryonic development is subjected to evolutionary pressures as much as other areas of the life cycle.

Cell biology is an area where many similarities can be seen between organisms. Many structures and pathways within the cell are vital for the continuance of life. The more important and basic to the whole structure of life a pathway or organelle is, the more likely it is to be observed. For example, the DNA code is the same in virtually all living organisms, as are such structures as mitochondria. These are virtually ubiquitous throughout known life. Most scientists hold that it is inconceivable that each of these things arose separately for each species of living organism. The conclusion advanced by science is that all life forms arose from the same basic source many millennia ago. The examples visible today have survived, and the organisms carrying these processes on have adapted, yielding the diversity of forms seen today.

See also Cosmology; Dating methods; Fossils and fossilization; Stratigraphy

EVOLUTIONARY MECHANISMS

Evolution is the process of biological change over time. Such changes, especially at the genetic level, are accomplished by a complex set of evolutionary mechanisms that act to increase or decrease genetic variation. Changes at the genetic level are often directly caused by physical phenomena (e.g., cosmic rays). Genetic changes are also indirectly acted upon by the physical environment in such a manner that the number of genetic changes (e.g., mutations) within a population can either increase or decrease in subsequent generations.

Evolutionary theory is the cornerstone of modern biology, and unites all the fields of biology under one theoretical umbrella to explain the changes in any given gene pool of a population over time. Fundamental to the concept of evolutionary mechanism is the concept of the syngameon, the set of all genes. By definition, a gene is a hereditary unit in the syngameon that carries information that can be used to construct proteins via the processes of transcription and translation. A gene pool is the set of all genes in a species or population.

Another essential concept, important to understanding evolutionary mechanisms, is an understanding that there are no existing (extant) primitive organisms that can be used to study evolutionary mechanism. For example, all eukaryotes (organisms having a true nucleus) derived from a primitive, common prokaryotic (organisms such as bacteria that lack a true nucleus) ancestral bacterium. Accordingly, all living eukaryotes have evolved as eukaryotes for the same amount of time. Additionally, no eukaryote plant or animal cell is more primitive with regard to the amount of time they have been subjected to evolutionary mechanisms. Seemingly primitive characteristics are simply highly efficient and conserved characteristics that have changed little over time.

Evolution requires genetic variation, and these variations or changes (mutations) can be beneficial, neutral, or deleterious. In general, there are two major types of evolutionary mechanisms—those that act to increase genetic variation, and mechanisms that operate to decrease genetic mechanisms.

Mechanisms that increase genetic variation include mutation, recombination and gene flow.

Mutations generally occur via chromosomal mutations, point mutations, frame shifts, and breakdowns in DNA repair mechanisms. Chromosomal mutations include translocations, inversions, deletions, and chromosome non-disjunction. Point mutations may be nonsense mutations leading to the early termination of protein synthesis, missense mutations (a mutation that results in a substitution of one amino acid for another in a protein), or silent mutations that cause no detectable change. Point mutations may result from natural phenomena such as cosmic radiation.

Recombination involves the re-assortment of genes through new chromosome combinations. Recombination occurs via an exchange of DNA between homologous chromosomes (crossing over) during meiosis. Recombination also includes linkage disequilibrium. With linkage disequilibrium, more variations of the same gene (alleles) occur in combinations in the gametes (sexual reproductive cells) than should occur according to the rules of probability.

Gene flow occurs when individuals change their local genetic group by moving from one place to another. These migrations allow the introduction of new variations of the same gene (alleles) when they mate and produce offspring with members of their new group. In effect, gene flow acts to increase the gene pool in the new group. Because genes are usually carried by many members of a large population that has undergone random mating for several generations, random migrations of individuals away from the population or group usually do not significantly decrease the gene pool of the group left behind.

In contrast to mechanisms that operate to increase genetic variation, there are fewer mechanisms that operate to decrease genetic variation. Mechanisms that decrease genetic variation include genetic drift and natural selection.

Genetic drift results from the changes in the numbers of different forms of a gene (allelic frequency) that result from sexual reproduction. Genetic drift can occur as a result of random mating (random genetic drift) or be profoundly affected by geographical barriers, catastrophic events (e.g., natural disasters or wars that significantly affect the reproductive availability of selected members of a population), and other political-social factors.

Natural selection is based upon the differences in the viability and reproductive success of different genotypes with a population (differential reproductive success). Natural selection can only act on those differences in genotype (type of genes present) that appear as phenotypic (visible characteristics) differences that affect the ability to attract a mate and produce viable offspring that are, in turn, able to live, mate and continue the species. Evolutionary fitness is the success of an entity in reproducing (i.e., contributing alleles to the next generation).

There are three basic types of natural selection. With directional selection, an extreme phenotype is favored (e.g., for height or length of neck in giraffe). Stabilizing selection occurs when intermediate phenotype is fittest (e.g., neither too high nor too low a body weight) and for this reason it is often referred to a normalizing selection. Disruptive selection occurs when two extreme phenotypes are fitter than an intermediate phenotype.

Natural selection does not act with foresight. Rapidly changing environmental conditions can, and often do, impose new challenges for a species that result in extinction. In addition, evolutionary mechanisms, including natural selection, do not always act to favor the fittest in any population, but instead may act to favor the more numerous but tolerably fit. Thus, the modern understanding of evolutionary mechanisms does not support the concepts of social Darwinism.

The operation of natural evolutionary mechanisms is complicated by geographic, ethnic, religious, and social groups and customs. Accordingly, the effects of various evolution mechanisms on human populations are not as easy to predict. Increasingly sophisticated statistical studies are carried out by population geneticists to characterize changes in the human genome.

See also Cosmic ray; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Radioactivity; Uniformitarianism

EXFOLIATION

Exfoliation is the term used to describe the peeling away of sheets of **rock** millimeters to meters in thickness from a rock's surface due a range of physical and chemical processes during exhumation and **weathering**. Exfoliation can occur due to several processes.

Unloading or release of stress in a rock that produces expansion joints can cause exfoliation. A reduction in stress occurs when rocks previously buried deeply are exposed due to **erosion** of overlying rocks, or when **ice** sheets that bury rocks melt. During a combination of physical and chemical weathering, exfoliation may occur parallel to a rock's outer surface due to a combination of chemical breakdown of **minerals**, especially in the presence of **water**. Such 'onion-skin' style weathering occurs especially in **igneous rocks** (e.g., **granite**) as micas, amphiboles and pyroxenes, common minerals in many igneous rocks, break down to **clay**. Clays swell in the presence of water, so alternating wetting and drying of a rock may lead to consecutive expansion and shrinking that can result in disintegration and exfoliation.

Stresses induced in a rock due to the expansion of water trapped between grains or in fractures in a rock during **freezing** may result in fracturing. Shattering of rock into small fragments by the expansion of water during the formation of ice is common in arctic environments (causing a problem for field geologists looking for rock relationships and structures). Likewise, changes in **temperature** of a rock may cause exfoliation. Stresses due to variability in the rates and amounts of expansion of different minerals in a rock, or due to alternating expansion and shrinkage from day to night in **desert** areas, may result in exfoliation. Rapid temperature changes may also occur due to lightning strikes followed by cooling in the ensuing rain. Although generally a naturally occurring process, exfoliation was also induced by man to obtain rock sheets several centimeters in thickness to thin, sharp shards of some fine-grained rocks for use as scrapers and knives by heating the rock with fire, then pouring water on the rock's surface.

See also Weathering and weathering series

EXTRUSIVE COOLING

Igneous rocks formed at ground level are termed extrusive. A body of extruded **magma** (molten **lava**) cools more rapidly than an equal amount of magma intruded into preexisting **rock** because all extruded magma is bathed, at least on its upper surface, in a coolant (e.g., air or **water**). Gobs of lava blown high into the air by a volcanic eruption may even solidify before reaching the ground, producing the streamlined, glassy rocks termed volcanic bombs. At the opposite extreme, a lava flow many yards thick may take days or weeks to crystallize all the way through and years to cool to ambient **temperature**. Even a thick lava flow, however, cools very rapidly compared to an intrusion of comparable dimensions, which may take hundreds or thousands of years to crystallize.

Fast cooling does not permit the formation of large **crystals**, so extrusive cooling produces either very fine-grained crystalline rock or volcanic **glass**, which contains no crystals at all. Because glasses are inherently unstable and spontaneously reorganize into fine-grained crystalline rocks over millions of years, truly old (pre-Cenozoic) glasses are rare.

Another feature of extrusive cooling is that **atmospheric pressure** is much lower than the pressures under which magmas form. Magma's volatile components, that is, those substances that tend to separate out at high temperature and low pressure (especially water), are therefore quickly lost by extruded magma, and are not present during crystallization. Reduced water content in a magma permits many **minerals** to crystallize at higher temperatures, further speeding the rapid crystallization caused by fast cooling.

See also Amorphous; Intrusive cooling; Lava; Volcanic eruptions; Volcano

F

FAHRENHEIT, DANIEL GABRIEL

(1686-1736)

Dutch physicist

Daniel Fahrenheit invented the first truly accurate thermometer using mercury instead of alcohol and **water** mixtures. In the laboratory, he used his invention to develop the first **temperature** scale precise enough to become a worldwide standard.

The eldest of five children born to a wealthy merchant, Fahrenheit was born in Danzig (Gdansk), Poland. When he was fifteen his parents died suddenly, and he was sent to Amsterdam to study business. Instead of pursuing this trade, Fahrenheit became interested in the growing field of scientific instruments and their construction. Sometime around 1707, Fahrenheit began to wander the European countryside, visiting instrument makers in Germany, Denmark, and elsewhere, learning their skills. He began constructing his own thermometers in 1714, and it was in these that he used mercury for the first time.

Previous thermometers, such as those constructed by Galileo and Guillaume Amontons, used combinations of alcohol and water; as the temperature rose, the alcohol would expand and the level within the thermometer would increase. These thermometers were not particularly accurate, however, since they were too easily thrown off by changing air pressure. The key to Fahrenheit's thermometer was a new method for cleaning mercury that enabled it to rise and fall within the tube without sticking to the sides. Mercury was an ideal substance for reading temperatures since it expanded at a more constant rate than alcohol and is able to be read at much higher and lower temperatures.

The next important step in the development of a standard temperature scale was the choosing of fixed high and low points. It was common in the early eighteenth century to choose as the high point the temperature of the body, and as the low point the **freezing** temperature of an ice-and-salt mixture, then believed to be the coldest temperature achievable in the laboratory. These were the points chosen by Claus Roemer, a German scientist whom Fahrenheit visited in 1701. Roemer's scale placed blood temperature at 22.5°F and the freezing point of pure water at 7.5°F. When Fahrenheit graduated his own scale he emulated Roemer's fixed points; however, with the improved accuracy of a mercury thermometer, he was able to split each degree into four, making the freezing point of water 30°F and the temperature of the human body 90°F. In 1717, he moved his points to 32°F and 96°F in order to eliminate fractions.

These points remained fixed for several years, during which time Fahrenheit performed extensive research on the freezing and boiling points of water. He found that the boiling point was constant, but that it could be changed as **atmospheric pressure** was decreased (such as by increasing elevation to many thousand feet above sea level). He placed the boiling point of water at 212°F, a figure that was actually several degrees too low. After Fahrenheit's death scientists chose to adopt this temperature as the boiling point of water and to shift the scale slightly to accommodate the change. With 212°F as the boiling point of water and 32°F as the freezing point, the new normal temperature for the human body became 98.6°F.

In 1742, Fahrenheit was admitted to the British Royal Society despite having had no formal scientific training and having published just one collection of research papers.

See also Temperature and temperature scales

FAHRENHEIT SCALE • *see* TEMPERATURE AND TEMPERATURE SCALES

FARADAY, MICHAEL (1791-1867)

English physicist and chemist

Michael Faraday's early life had a remarkable resemblance to that of **Benjamin Franklin**. Faraday was born in Newington, Surrey, England. Like Franklin, Michael Faraday was part of a large family. His father was a blacksmith who lacked the resources to obtain a formal education for his son.

Franklin had been apprenticed to a printer; young Faraday went a similar route, becoming apprenticed to a bookbinder. In each case, this led to a voracious love of books. Michael was especially interested in **chemistry** and **electricity**. He studied the articles about electricity in the *Encyclopaedia Britannica*. His employer not only allowed him to read all that he wanted, he encouraged the boy to attend scientific lectures.

A turning point occurred in 1812. In that year, Faraday obtained tickets to hear the lectures of Humphry Davy at the Royal Institution. Faraday took careful notes extending to 386 pages, which he had bound in leather. He sent a copy to Sir Joseph Banks (1743–1820), president of the Royal Society of London, who wielded great influence over European scientific investigation. Faraday hoped to make a favorable impression, but if Banks ever looked through the book with its carefully drawn and colored diagrams, Faraday never knew it.

Determined not to be ignored, Faraday sent a copy of his notes to Davy and included an application for a job as Davy's assistant. Davy was impressed, but did not offer Faraday work as he already had an assistant. Later, however, after firing the assistant in 1813, Davy contacted Faraday. The job description was not quite what Faraday had in mind. A trustee of the Royal Institution had said, "Let him wash bottles. If he is any good, he will accept the work; if he refuses, he is not good for anything." Faraday accepted, even though it meant he would be paid less than what he was making as a bookbinder.

Shortly thereafter, Davy resigned his post at the Royal Institution, married a wealthy widow, and decided to travel through **Europe**. Faraday accompanied the couple and met such illustrious men as Italian physicist Alessandro Volta and French chemist Louis-Nicholas Vauquelin.

In 1820, Danish Physicist Hans Christian Oersted amazed scientists with the discovery that electric current produced a **magnetic field**. Faraday had a greater goal in sight: Oersted had converted electric current into a magnetic force; Faraday intended to reverse the process and create electricity from **magnetism**. Within a year Faraday, now back in England, constructed a device that essentially consisted of a hinged wire, a magnet and a chemical battery. When the current was turned on, a magnetic field was set up in the wire, and it began to spin around the magnet. Faraday had just invented the electric motor. Faraday's motor was certainly an interesting device, but it was treated as a toy.

At this point, Davy, realizing that Faraday had the potential to eclipse him, jealously claimed that Faraday had taken his own idea for the experiment.

Faraday's first major contribution to chemistry came a few years later. In 1823 he unknowingly became the "father" of cryogenics by producing laboratory temperatures that were below **freezing**. He discovered how to liquefy **carbon dioxide**, chlorine, hydrogen sulfide, and hydrogen bromide gases by placing them under pressure, but again Davy took the credit. Two years later Faraday discovered the compound benzene, which became his greatest contribution in chemistry. In 1865 German chemist Friedrich Kekulé was able to determine the structure of benzene, leading to the understanding of molecular structure in general.

The studies of **magnetism** and electricity were still main interests of Faraday, so he elaborated on Davy's pioneering work in electrochemistry. Davy had passed an electric current through a variety of molten **metals** and created new metals in the process. Faraday named this process electrolysis. He also bestowed names that were suggested by the British scholar Whewell and are still in use today: electrolyte, for the compound or solution that conducts electricity; electrode, for the metal rod inserted in the object; and anode and cathode for the positively and negatively charged electrodes, respectively.

In 1832, Faraday devised what became known as Faraday's laws of electrolysis, which hold that the mass of the substance liberated at an electrode during electrolysis is proportional to the amount of electricity going through the solution; and the mass liberated by a given amount of electricity is proportional to the atomic weight of the element liberated and inversely proportional to the "combining power" of the element liberated. The two laws showed there was a connection between electricity and chemistry. They also supported the suggestion that Franklin had made nearly 100 years earlier when he claimed electricity was composed of particles, a theory that would be another 50 years in the making.

In another experiment, Faraday sprinkled **iron** filings on a paper which was held over a magnet and noticed the filings had arranged themselves along what he called "lines of force." The connections along the lines showed where the strength of the field was equal. With the magnetic field now "visible," scientists began to wonder if **space** itself was filled with interacting fields of various types and this helped establish a new way of thinking about the universe. Up to this point most scientists had believed in the mechanical nature of the universe as established by Galileo and Isaac Newton.

Taking the concept of his lines of force one step farther, Faraday realized that when an electric current began to flow it caused lines of force to expand outward. When the current stopped, the lines collapsed. If the lines expanded and collapsed across an intervening wire, an electric current would be induced to flow through it, first forward then in reverse.

By now Faraday was giving public lectures, which were very popular, at the Royal Institute, just as Davy had. Faraday reasoned that if electricity could induce a magnetic field, then it should be possible for the reverse to be true. Taking an iron ring during one demonstration, Faraday wrapped half of it with a coil of wire that was attached to a battery and switch. André Ampère (1775–1836) had shown that electricity would set up a magnetic field in the coil. The other half of the ring was wrapped with a wire that led to a galvanometer. In theory, the first coil would set up a magnetic field that the second coil would intercept and convert back to electric current, which the galvanometer would register. Faraday threw the switch: the experiment worked. He had just invented the transformer. However, the result was not exactly what he expected. Instead of registering a continuous current, the galvanometer moved only when the circuit was opened or closed. Ampère had observed the same effect a decade earlier but ignored it because it did not fit his theories. Deciding to make the theory fit the observation, instead of the other way around, Faraday concluded that when the current was turned on or off, it caused magnetic “lines of force” from the first coil to expand or contract across the second coil, inducing a momentary flow of current in the second coil. Faraday had now discovered electrical induction. Meanwhile, in the United States, physicist Joseph Henry had independently made the same discovery.

In 1839, at the age of 48, Faraday had a nervous breakdown. Faraday never completely recovered. It is also possible that he was afflicted with a low-grade chemical poisoning. This was a common ailment that affected chemists at the time; Davy had suffered from it as well. In any event, Faraday’s failing memory forced him to leave the laboratory.

Faraday published a book describing his lines of force in 1844, but because he lacked a formal education it was written without mathematical equations. Consequently the book was not taken seriously. When **James Clerk Maxwell** investigated the subject, he essentially came to the same conclusion as Faraday had, but used mathematics to prove his theory.

Although out of the laboratory, Faraday was by no means inactive. He investigated the effect of weak magnetic fields on nonmetallic substances and coined the words paramagnetic and diamagnetic to differentiate between the force of attraction and repulsion. Development of a theory to explain the two opposing forces, however, had to wait more than 50 years for the work of Paul Langevin. In the 1850s, during the Crimean War, the British government sought his opinion on the feasibility of using poisonous chemical weapons, and asked him to oversee their development. Faraday immediately said the project was very feasible, but he refused to have anything to do with its initiation.

Faraday died at Hampton Court, Middlesex, England. The word “farad,” which is a unit of capacitance, was named in his honor.

See also Electricity and magnetism; Electromagnetic spectrum

FAULTS AND FRACTURES

Fractures and faults are planes of tensile or shear failure at microscopic to regional scales in brittle rocks. Faults may constitute a single plane or comprise zones of parallel or oblique shear planes, fault **breccia** or gouge (finely ground **rock**) across which there has been relative displacement of rocks on either side. Faults and fractures dominate approximately the upper 9 mi (15 km) of the earth’s **crust**. Earthquakes are the expression of rapid displacement along faults. Most upper crustal rocks deform in a brittle manner at rapid deformation (strain) rates due to low **temperature** and confining pressure. Faults and fractures also develop in competent rocks at deeper crustal levels and in some dry rocks in the lower crust.

Fractures develop when the applied stress exceeds a rock’s elastic limit. Regional stresses in plate interiors responsible for fracturing and faulting may represent far-field effects of tectonic forces acting on plate margins. They can also result from gravitational instabilities (e.g., when a less dense, ductile rock such as salt is overlain by brittle, denser rocks), unloading (e.g., in response to removal of an **ice** sheet) or **mantle plumes**. Rocks may also fracture at regional stresses below their elastic limit if pore fluid pressure increases sufficiently. This phenomenon (called hydrofracturing or hydraulic fracturing) is used commercially in the **petroleum** industry to increase **permeability** of petroleum reservoirs. It may also be induced inadvertently, such as by building a large dam over a previously inactive fault zone, triggering fracturing that may potentially cause the dam to fail.

The San Andreas fault is a famous example of a strike-slip fault. ***Photograph by Robert E. Wallace. U.S. Geological Survey.***

Tensile (extensional) fractures develop normal to the maximum extension direction. Tensile fractures may dilate and infill with **minerals** such as **quartz** and calcite precipitated from fluids within the rock to form extensional veins. The direction of vein opening (deduced from the orientation of quartz or calcite fibers that track the incremental extension direction) is orthogonal to fracture margins. Shear fractures (fractures along which lateral displacement occurs) develop oblique to the principal stresses. Shear fractures commonly develop in two preferred orientations where fractures with the opposite sense of displacement form at an angle of approximately 60° to each other, constituting a conjugate set. Conjugate fractures are bisected acutely by the maximum shortening direction and obtusely by the maximum extension direction. Their intersection parallels the intermediate principal stress. The acute angle between conjugate shear fractures and faults may be less than 60° if the rock is very brittle or greater than 60° if the rock is more ductile. One or more of the following types of minor fractures commonly develop prior to the formation of through-going shear fractures or faults:

- tensile fractures that **strike** parallel to each other in both conjugate zones,
- shear fractures along each zone that trend parallel to, and have the same sense of displacement as the conjugate zone,
- shear fractures (called Riedel shears) that make an angle of approximately 15° to each zone.

All three may step en échelon along incipient **shear zones**. The sense of stepping may be used to determine the sense of displacement along a fault where there is no clear offset of marker layers.

There are three end-member types of faults, with each type forming under different orientations of principal stresses:

- Normal or extensional faults are inclined structures along which rocks above the fault plane (i.e. in the hangingwall) are displaced down the fault with respect to rocks beneath the fault plane (i.e. in the footwall). Such faults were called normal as they were the most commonly observed faults by Welsh **coal** miners who termed the name. They form when the maximum extension direction is horizontal during vertical shortening (due to the gravitation loading of overlying rock). Normal faults develop in sedimentary basins during **rifting** and in areas of localized horizontal extension, such as above salt diapirs or during collapse or slumping.
- Reverse or contractional faults are moderately inclined structures along which the hanging wall is displaced up the footwall. The name reverse fault also comes from Welsh miners as they showed the opposite sense of displacement to the normal faults. Shallowly dipping faults with reverse displacement are called thrusts. Reverse and thrust faults imply horizontal shortening and vertical extension, and are commonly formed in convergent plate margins. Reverse faults in sedimentary basins may also form in the toes of deltas because of local shortening due to sediment loading or slumping or on the margins of laterally expanding salt diapirs.
- Faults along which there has been lateral, sub-horizontal displacement are called strike-slip, transcurrent or wrench faults. They are generally steeply dipping structures. They also form during regional horizontal shortening, but where the maximum extension direction is horizontal. When the left side (observed in map view) is displaced towards the observer, the fault is said to show a sinistral or left lateral sense of displacement. When the right side is displaced towards the observer, the displacement is dextral or right-lateral.

Oblique-slip faults have components of both transcurrent and either normal or reverse displacement. The direction of displacement along a fault is indicated by fine scratch or gouge marks (called slickenlines) and/or mineral fibers that infill spaces created by displacement of irregular, stepped surfaces. Fault planes that contain striations and/or fibers are called slickensides. Where the sense of displacement cannot be seen by the offset of markers, it can be determined from the sense of stepping of irregularities along the fault surface, the location of dilatational sites in which mineral fibers have grown, gouge marks formed by the incutting of rigid bodies in the rock, and the en échelon stepping of minor fractures (as described above).

Faults are important in mineral and petroleum exploration as they may either seal and act as a barrier to fluid flow (e.g., due to smearing of mud or shale along them), or may be important conduits for the migration of petroleum or mineralizing fluids. Many mineral deposits are fault and fracture controlled. Recognition of faults is also important in hydrogeological studies as fracturing along faults may produce hard-rock aquifers.

See also Petroleum detection; Plate tectonics

FAUNAL SUCCESSION • *see* FOSSIL RECORD

FELDSPAR

Feldspar is the most common mineral on Earth, constituting approximately 60% of the **crust**. It forms directly from cooling **magma** and is a major component of **granite** and most other **igneous rocks**.

The term feldspar actually covers a whole family of **minerals**, all of which consist of a framework of **aluminum**, **oxygen**, and **silicon** atoms plus an additive, usually potassium, sodium, or calcium. Feldspars vary in color from pink to gray, and are categorized by the additives they contain. Pure potassium feldspar is orthoclase ($KAlSi_3O_8$), pure sodium feldspar is albite ($NaAlSi_3O_8$), and pure calcium feldspar is anorthite ($CaAl_2Si_3O_8$). A feldspar may contain both sodium and calcium or sodium and potassium. The sodium–calcium feldspars form a continuum from albite to anorthite, the **plagioclase** feldspar series, which corresponds to the continuous branch of **Bowen's reaction series**. The sodium–potassium feldspars form a continuum from albite to orthoclase that is termed the orthoclase or alkali feldspar series. Feldspars containing significant quantities of both calcium and potassium are not found, as such mixtures are not chemically stable in cooling magma and react to form other minerals.

Orthoclase feldspars cleave along two planes that are at right angles, and plagioclase feldspars cleave along two planes that are not quite at right angles. Feldspar nomenclature is based on these mechanical properties: *ortho*, *plagio*, and *clase* are the Greek for right, slanted, and breaking, respectively.

Feldspar is less chemically stable when exposed to **water** than **quartz**, the other major ingredient of granite. Granite exposed to **weather** therefore becomes crumbly as its feldspar decays, and mechanical forces (e.g., **wind**, running water) break the granite up into **sand**. Rough, rapid fragmentation liberates some feldspar before it has had time to decay chemically, so a sand's ratio of feldspar to quartz records the rate at which its source granite was fragmented. This information is used by geologists to deduce ancient patterns of mountain-building and **erosion**.

See also Weathering and weathering series

FELSIC

Geologists sometimes find it useful to classify **igneous rocks** based on color. Because color is sensitive to minor chemical differences it is not a very reliable index to the history or composition of any given **rock**; however, it has the merit of being obvious at a glance, making color classification an indispensable aid to describing rocks in the field. **Minerals** are classed in two general color groups: felsic (light) and **mafic** (dark). Rocks may contain a mixture of mafic and felsic minerals, and are termed felsic if felsic minerals predominate, mafic otherwise. Alternatively, a numerical color index can be assigned to a rock based on visual estimation of the percentage of mafic or felsic minerals it contains.

Felsic minerals are usually higher in silica (SO_2) and **aluminum** and of lower density than mafic minerals. Common felsic minerals are **quartz**, **feldspar**, and the feldspathoids, and common felsic rocks (i.e., rocks high in felsic minerals) are **granite** and **rhyolite**. Mafic minerals are usually higher high in **iron** and magnesium than felsic minerals; common mafic minerals are pyroxene, amphibole, **olivine**, mica, and biotite, and common mafic rocks are **basalt** and gabbro.

The term mafic is also used in a precise chemical sense, that is, to denote rocks consisting of 45–52% silica regardless of color. Since the non-silica fraction of a rock often consists largely of iron and magnesium compounds, rocks that are mafic in the chemical sense are usually also mafic in the color sense.

See also Silicic

FERREL'S LAW

Ferrel's law, named after American meteorologist W. Ferrel (1817–1891), is the rule that air or **water** moving horizontally in the Northern Hemisphere is deflected or pushed to the right of its line of motion while air or water moving horizontally in the Southern Hemisphere is deflected to the left of its line of motion. Ferrel's law, which predicts the directions of the large-scale circulations of the earth's atmosphere and **oceans**, is a restatement in global terms of the action of the Coriolis force.

The Coriolis force is a consequence of the conservation of angular momentum and arises as follows. Consider a spinning disk with an ant perched on its outer edge. The ant's angular momentum (P) is given by its mass (m) times the square of its distance from the center of the disk (r^2) times the radial velocity of the disk (ω, how fast it is turning): $P = mr^2\omega$. If the ant crawls along a straight radial line toward the center of the disk, its radial velocity ω—the number of turns around the axis it makes per second—remains constant. Its mass m also remains constant. However, its distance from the center r decreases. By the above formula, therefore, its angular momentum P also decreases. Yet a force is required to change the angular momentum of an object. Therefore, as it walks straight toward the center of the disk the ant must experience a force (a sideways push on its feet) that decelerates its rate of spin. From the perspective of the ant, the result is straight-line relative to the disk, and this sideways push seems required to balance a force tending to accelerate the ant sideways in the direction of the disk's **rotation**. This apparent force, which only seems to act while the ant is in motion toward or away from the disk's axis of rotation (i.e., is changing its angular momentum), is termed the Coriolis force. If the surface of the disk is too slippery to enable the moving ant to completely resist this apparent force, the ant will be deflected by it, relative to the disk's surface, in the direction of the disk's spin: that is, it will retain some or all of its original angular momentum by rotating more rapidly as it nears the disk's axis of rotation, just as a spinning ice skater's limbs rotate more rapidly as she or he retracts them toward her or his axis of rotation.

An ant trying to crawl axisward on a slippery disk is like a body of the air trying to drift northward or southward on the spinning (rotating) earth. Because Earth rotates eastward, air moving toward the axis of rotation (i.e., toward either the North or South Pole) tends to preserve its angular momentum by accelerating eastward; that is, it experiences an eastward Coriolis force that deflects it in the direction described by Ferrel's law. Eastward acceleration of a north-moving object in the Northern Hemisphere is to the right, as viewed along the object's line of motion; of a south-moving object in the Southern Hemisphere, to the left. Movements *away* from the axis of rotation are deflected *westward* in both hemispheres—again, to the right of the line of motion in the north, to the left in the south. The result is that high pressure systems, as seen from **space** tend to spin clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Low pressure systems spin in the respective reverse direction.

Ferrel's law applies equally to air and ocean movements, so the oceans circulate in the same sense as the air in both hemispheres. However, though it is often said to do so, Ferrel's law does not govern the direction of whirlpool spin in draining sinks and toilets. The Coriolis force is too weak to determine the behavior of fluids in such small basins.

See also Silicic

FERROMAGNETIC

Iron, cobalt, nickel, and various alloys of these materials are called ferromagnetic. Ferromagnetic materials can be permanently magnetized through exposure to an external **magnetic field**. They are strongly drawn towards a magnetic field. Their magnetic susceptibility, which is a material specific constant that relates applied field and magnetic response linearly, is orders of magnitude stronger than the susceptibility of paramagnetic or diamagnetic materials.

Paramagnetic materials are drawn towards magnets, while diamagnetic materials are repelled. Neither material can become permanently magnetized—or carry a remanent magnetization—and this is independent of **temperature** for all practical purposes. Their magnetic susceptibility is weakly positive and negative, respectively. The strength of a material's magnetic susceptibility is solely dependent on crystal structure. Paramagnetism usually dominates over diamagnetism. Most **rock** forming **minerals** are diamagnetic (e.g., **quartz**, **limestone**) or paramagnetic (e.g., micas, amphiboles).

Ferromagnetic behavior is different from diamagnetism and paramagnetism in several respects. First, it is strongly dependent on temperature. A ferromagnet looses its ability to carry a remanent magnetization and simply become paramagnetic if heated above its specific Curie temperature. A second fundamental property of ferromagnets is hysteresis. Hysteresis means that the application of an external field changes a ferromagnet irreversibly. The magnetic state of a ferromagnet depends not only on the strength of an applied field, but also on the history of the magnet. Any applied field can produce four different magnetic answers in a ferromagnet, once it has been magnetized initially. Additional to their susceptibility, ferromagnets are characterized by their coercivity, which is proportional to the field strength necessary to remagnetize it, and by their saturation remanence.

The most important variants of ferromagnetism are ferromagnetism and antiferromagnetism. Magnetite is the most abundant representative of the first family. It is a product of abiotic geochemical processes. Pure magnetite can be grown inter- and extra-cellularly by bacteria. These iron-oxide minerals have different crystal lattices resulting in dramatically differing magnetic properties. An important antiferromagnetic mineral is goethite, which is a product of **weathering** processes.

The properties of ferromagnets are not only determined by their crystalline structure, but also depend strongly on the grain-size of a particle. Ferromagnets develop magnetic domains above a critical volume. They are not capable of having a remanent magnetization below this volume, in which case they are called superparamagnetic. Magnetization carried by particles just above the critical threshold are extremely stable, because these single domain particles can only be magnetized parallel to their long, easy, axis. A further increase of the particle volume leads to the development of an increasing number of domains that destabilizes the remanent magnetization.

Both palaeomagnetic and rock magnetic research use the ferromagnetic properties of rocks. Palaeomagnetism uses the fact that minute amounts of ferromagnets acquire a magnetization parallel to the magnetic field of the earth at the time of the rocks' formation. This naturally occurring magnetization of rocks can be used in **plate tectonics** and magnetostratigraphy to reconstruct the former distribution of tectonic plates and continents, and to date sedimentary sequences.

Rock magnetic research uses the fact that it is relatively easy to measure the ferromagnetic properties of rocks. Additionally, rock **magnetism** is a fast and non-destructive method. Because composition and grain size distribution of any assemblage of iron-oxide minerals is a highly sensitive indicator of past environmental change, rock **magnetism** has become ever more important in environmental and palaeoclimatic research. Today, environmental magnetism is routinely incorporated in research projects designed to understand the environmental history of a site, material or region.

See also Paleomagnetics

FERSMAN, ALEKSANDR EVGENIEVICH
(1883-1945)
Russian geochemist

Aleksandr Evgenievich Fersman was a Russian geochemist and mineralogist. He made major contributions to Russian **geology**, both in theory and exploration, advancing scientific understanding of crystallography and the distribution of elements in the earth's **crust**, as well as founding a popular scientific journal and writing biographical sketches of eminent scientists. He was known as a synthesizer of ideas from different subdisciplines.

Fersman was born in St. Petersburg on November 8, 1883, to a family that valued both art and science. His father, Evgeny Aleksandrovich Fersman, was an architect and his mother, Maria Eduardovna Kessler, a pianist and painter. Fersman's maternal uncle, A. E. Kessler, had studied **chemistry** under Russian chemist Aleksandr Mikhailovich Butlerov.

At the family's summer estate in the Crimea, Fersman first discovered **minerals** and began to collect them. When his mother became ill, the family traveled to Karlovy Vary (Carlsbad) in Czechoslovakia. There the young Fersman explored abandoned mines and added to his collection of **crystals** and druses (crystal-lined rocks).

Fersman graduated from the Odessa Classical Gymnasium in 1901 with a gold medal and entered Novorossisk University. He found the **mineralogy** course so dull that he decided to study art history instead. He was dissuaded by family friends (the chemist A. I. Gorbov and others) who encouraged him to delve into molecular chemistry. He subsequently studied physical chemistry with B. P. Veynberg, who had been a student of Russian chemist Dmitri Ivanovich Mendeleev. Veynberg taught Fersman about the properties of crystals.

The Fersman family moved to Moscow in 1903 because Aleksandr's father became commander of the First Moscow Cadet Corps. Fersman transferred to Moscow University, where his interest in the structure of crystals continued. Studying with mineralogist V. I. Vernadsky, he became an expert in goniometry (calculation of angles in crystal) and published seven scientific papers on crystallography and mineralogy as a student. When Fersman graduated in 1907, Vernadsky encouraged him to become a professor.

By 1908, Fersman conducted postgraduate work with **Victor Goldschmidt** at Heidelberg University in Germany. Goldschmidt sent him on a tour of Western **Europe** to examine the most interesting examples of natural **diamond** crystals in the hands of the region's jewelers. This work formed the basis of an important monograph on diamond crystallography Fersman and Goldschmidt published in 1911.

While a student in Heidelberg, Fersman also visited French mineralogist François Lacroix's laboratory in Paris and encountered pegmatites for the first time during a trip to some islands in the Elbe River that were strewn with the rocks. Pegmatites are granitic rocks that often contain rare elements such as uranium, tungsten, and tantalum. Fersman was to devote years to their study later in his career.

In 1912, Fersman returned to Russia, where he began his administrative and teaching career. He became curator of mineralogy at the Russian Academy of Science's Geological Museum. He would be elected to the Academy and become the museum's director in 1919. During this period Fersman also taught **geochemistry** at Shanyavsky University and helped found *Priroda*, a popular scientific journal to which he contributed throughout his life.

Fersman participated in an Academy of Science project to catalogue Russia's natural resources starting in 1915, traveling to all of Russia's far-flung regions to assess mineral deposits. After the Russian Revolution, Lenin consulted Fersman for advice on exploiting the country's mineral resources. During World War I Fersman consulted with the military, advising on strategic matters involving geology, as he would also later do in World War II.

In the early 1920s, Fersman devoted himself to one of geochemistry's major theoretical questions regarding the distribution of the **chemical elements** in the earth's crust. Fersman worked out the percentages for most of the elements and proposed that these quantities be called "clarkes" in honor of Frank W. Clarke, an American chemist who had pioneered their study. Clarkes had traditionally been expressed in terms of weight percentages; Fersman calculated them in terms of atomic percentages. His work showed different reasons for the terrestrial and cosmic distribution of the elements. He was interested in the ways in which elements are combined and redistributed in the earth's crust. He coined the term "technogenesis" for the role of humans in this process, concentrating some elements and dispersing others through extraction and industrial activities.

Over the next twenty years, Fersman was responsible for a reassessment of the U.S.S.R.'s mineral resources. There were many areas, such as Soviet Central **Asia** and Siberia, which were thought to be resource-poor. Fersman showed otherwise, traveling from the Khibiny Mountains north of the Arctic Circle near Finland to the Karakum **Desert** north of Iran. He found rich deposits of apatite (a phosphorus-bearing mineral useful in fertilizers) in the former and a lode of elemental sulfur in the latter.

Fersman was acutely aware of the history of his profession and of science in general, passing on to his students his respect for his predecessors, especially Mendeleev and Vernadsky. He wrote many biographical sketches of distinguished scientists and published a number of popular works on mineral collecting. He was active in the Academy of Science of the U.S.S.R., serving in five different administrative posts, and received a number of honors, including the Lenin Prize. He died in the Soviet Georgian city of Sochi on May 20, 1945.

See also Earth, interior structure; Mineralogy

FEYNMAN, RICHARD (1918-1988)

American physicist

Richard Feynman's career spanned some of the greatest discoveries of twentieth century **physics**, from developing the atomic bomb and studying **quantum electrodynamics** (**QED**) to solving the riddle of the **space shuttle** *Challenger* disaster.

Feynman received the 1965 Nobel Prize for his work regarding the interaction of light and matter, which he shared with Shin'ichio Tomonaga and Julian Schwinger. Other honors he received include the **Albert Einstein** Award (1954), the **Niels Bohr** International Gold Medal (1973) and membership in the National Academy of Sciences (1954).

Richard Phillips Feynman was born in Queens, New York. His parents were Lucille Phillips and Melville Feynman, a clothing salesman originally from Minsk. Feynman was interested in science from an early age, when he tinkered with crystal radio sets. His father had predicted that his first child, if a boy, would be a scientist; Mr. Feynman got more than he bargained for, for Richard's younger sister Joan also became a physicist

Feynman attended New York public schools, and after high school graduation went on to study physics at the Massachusetts Institute of Technology. After receiving his bachelor's degree in 1939, he went on to do his doctoral work at Princeton, where he served as a research assistant to John A. Wheeler, a Nobel-Prize-winning physicist. As a graduate student under Wheeler, he concerned himself with the knotty problem of how electrons interact, a question that would occupy him for years.

During the 1920s, Paul Dirac had introduced the theory that described the behavior of electrons in such a way that satisfied both quantum mechanics and Albert Einstein's theory of relativity. However, many problems arose with Dirac's equation when the known principles governing electromagnetic interactions were brought to bear on it; then Dirac's equation involved dividing by zero, which resulted in infinite answers, which were for all practical purposes useless.

Feynman—who from his undergraduate days had a well-deserved reputation for finding better ways to complete calculations—found a way to circumvent these useless answers. By "renormalizing" or redefining, the existing value of the electron's mass and charge, he was able to make irrelevant the parts of Dirac's theory that led to the troublesome answers.

But Feynman's work did more than just clean up some messy mathematics. It also provided physicists a new way to work with electrons. It opened the way for a new examination and description of the hydrogen **atom**. It gave scientists a look at what really happens when electrons, anti-electrons (or positrons) and photons (light particles) collide.

Richard Feynman. ***Library of Congress.***

After receiving his doctorate, Feynman and his wife, Arlene Greenbaum, moved to Los Alamos, N.M., where he went to work with the Manhattan Project. There he worked, and held his intellectual own, with noted scientists such as Enrico Fermi and Hans Bethe, who headed Feynman's division. Feynman's wife Arlene, who had been his high-school sweetheart, died in 1945 after battling lymphatic tuberculosis. Less than a month after Arlene's death, Feynman became one of the first people in the world to witness the explosion of an atomic bomb.

After World War II, Bethe offered Feynman a position at Cornell University. While teaching physics, he also studied the question of the interaction of light and matter. In his description of the problem, he discarded the effect of the electromagnetic field and concentrated on the interactions of the particles themselves, as ruled by least action. In 1945, he also created a visual way to keep track of the interactions of the particles within time and **space**. Read from the bottom up (which indicates the passage of time), the diagrams show incoming particles (electrons) as straight lines. Their interactions (when they meet) are illustrated with wavy lines, indicating photons, which transmit the interactions. The straight lines then resume, indicating the departing particles after the interaction. Known as Feynman diagrams, they are still in use by theoretical physicists in such diverse areas as acousto-optics, QED, and studies of electroweak interactions.

Feynman left Cornell in 1950 to join the California Institute of Technology, or CalTech, with which he would be affiliated for the rest of his life. During his time at CalTech he turned his prodigious mind and imagination to a staggering variety of problems, including the superfluidity of helium, superconductivity, and quark theory.

He married again in 1952, to Mary Louise Bell; they divorced four years later. In 1960, he married again, for the last time, to Gweneth Howarth; the couple had two children.

In 1979, Feynman was diagnosed with cancer, which he would battle for the next decade, before his death at age 69. During his last decade, Feynman became one of the world's most popular scientists, with the publication of two autobiographies, *"Surely You're Joking, Mr. Feynman!" Adventures of a Curious Character* (1984) and *"What Do You Care What Other People Think?" Further Adventures of a Curious Character* (1988). He also published *QED: The Strange Theory of Light and Matter* in 1985. During the 1960s, he published *Quantum Electrodynamics* (1961), *The Character of Physical Law* (1965), and *The Feynman Lectures,* three volumes of transcribed physics lectures he gave at CalTech that beautifully explain everything from the fall of **water** to QED.

Feynman was part of the group that investigated the explosion of the space shuttle *Challenger* in 1986. Feynman memorably demonstrated the failure of the shuttle's O-ring gaskets by placing a piece of gasket in a clamp and dropping it into **ice** water. The material became brittle, and the simple demonstration showed that the gaskets' failure had caused the explosion.

See also Bohr Model; Electromagnetic spectrum; Quantum theory and mechanics

FIELD METHODS IN GEOLOGY

Geology is, at heart, a field science. Even though much work is done in the laboratory and at the computer, geological samples and information must initially be obtained from the context in which they occur in nature. This natural setting would typically be a field locale chosen by the investigating geologist, or by his employers.

The main field instruments used by geologists include the Brunton compass (and/or Silva compass), tape measures, and plane table and alidade. The Brunton compass is a compact device that permits compass bearings to be made upon linear features (including strike lines) and lines connecting any two points. The Brunton may also function as a protractor (when placed upon a map) and as a device for measuring structural **dip** and vertical angles (using its internal clinometer). The Silva compass is somewhat similar, except that it does not have a bubble level or adjustable clinometer, so a task like measuring a vertical angle is not possible, and **strike and dip** measurements may not be as accurately made as with a Brunton. This Silva does not come in a rugged case, as does the Brunton, but its design as a flat, blade shape allows it to be used for map work more easily than a Brunton. The geologist's tape measure is usually the reel-in variety, which is marked in meters and feet. A typical tape length is 100 ft (30.5 m). The plane table and alidade are surveying devices used to measure distance and relative elevation. The plane table sits atop a tripod and a geological or topographic map under construction would be taped to its top. The alidade is a telescopic device that can be moved over the map surface as sightings are made. This device allows measure of horizontal distance and elevation. Horizontal distance and elevation of a point on the earth's surface is obtained by viewing through the alidade sight, a rod with a printed scale upon it (called a *stadia*). Data recorded during this observation are used for recording distance and elevation of the surveyed point upon a map.

The field instruments above would accompany most fully equipped field geologists on an expedition of mapping and sample collection. The geologist would typically also carry along a field notebook, hand lens, hammer, acid bottle, knife, shovels or trowels, sample bags, pens and pencils, aerial photographs and **satellite** imagery, maps and literature, camping equipment, and a camera. In the modern era, these materials could also be supplemented by a global positioning satellite system (**GPS**) receiver (for determining location and retracing routes), laptop computers, digital cameras, and portable geophysical equipment (including a gravimeter, altimeter, magnetic susceptibility meter, etc.). Occasionally, a geologist will bring along power tools for cutting or drilling **rock** or plaster, and burlap for wrapping delicate samples such as fossil bones.

Field methods in geology may be broken down into four main groups: (1) obtaining and marking samples and describing and measuring where they came from in an outcrop; (2) measuring and recording orientation (i.e., altitude) of strata or other planar features; (3) measuring dimensions (height and width); and (4) constructing geologic and topographic maps.

Obtaining and marking samples and describing and measuring where they originate in an outcrop requires observational skills and patience to record all information that might be obtained at one outcrop. Typically, the thickness of strata at an outcrop is recorded in a notebook where the layers are drawn to scale and described as to rock type, grain size, fossil content, color, sedimentary structures, and other attributes. Thickness of strata is measured using a tape measure or a Jacob's staff, which is a long stick made for sighting intervals of equal stratigraphic thickness (usually 5 ft, or 1.5 m). In the field notebook, detail is given about sampling locations and where photographs of the rocks are made. Samples are marked with an arrow indicating 'up' direction and labeled with a number which relates to the notebook number for the outcrop plus a number relating to feet or meters above the base of the stratigraphic section at that location. The same process is followed at each locale. Later, this information is compiled into a measured and described section for each outcrop, which may be used for **correlation** between outcrops. In terrains where igneous and metamorphic rocks occur, it is usually not so important for sample information to be recorded about the up direction and elevation above the base of outcrop.

A geologist scoops pahoehoe lava from a Hawaiian flow. © *Roger Ressmeyer/Corbis. Reproduced by permission.*

Measuring and recording orientation (i.e., attitude) of strata or other planar features is another important field activity that relates to understanding geological structures and to the making of geological maps. Strike, dip direction, and dip magnitude of rock layers and other planar geological features (e.g., foliation) are obtained in as many places as possible within a study **area** in order to understand completely all the geological structures (i.e., **folds** and fault patterns) of an area. Analysis of geological structures can help geologists interpret the conditions of deformation of rocks in an area. Generally, the geologist tries to obtain as many orientation or attitude measurements as possible in the field area being studied.

Measuring dimensions (height and width) of an area or of features in an area, is an important aspect of many geological studies. This may be done as an estimate by using the moveable clinometer in a Brunton compass and employing trigonometric relationships to compute the height or width. For example, if one uses a tape measure (or number of foot paces, if the average foot pace of the observer is known) to measure distance to a cliff wall, and then uses the clinometer in his Brunton to measure angle between his eye level and the top of the cliff, a computation of cliff height can be made. In this instance, the cliff height is equal to the person's eye height plus the product of the horizontal distance to the cliff times the tangent of the sighted angle. Geologists sometimes make simple maps, called “pace and compass maps,” using the Brunton compass to take bearings and his measured pace length as a distance measure.

Constructing geologic and topographic maps is another field activity that occupies geologists. Geological maps are made by using a base map or set of aerial photographs to record the observed rock type (preferably a measured and described section, as noted above) and rock attitude at numerous locales in the study area. It is the task of the geologist to ultimately fashion a **geologic map** that is the simplest interpretation of all the surficial data about rock type and rock attitude in the area. Topographic maps are made by plane table and alidade, as noted above, and these may form the base map for geological mapping studies because surficial elevation is important in interpreting physical relationships between rock formations.

Other types of geological field work include reconnaissance studies of areas where detailed mapping is yet to be done, geological sample analysis conducted on-site at drilling operations, geophysical studies (where the objective is to collect data such as **gravity** strength, magnetic characteristics, etc.), surface- and ground-water studies (where the emphasis is upon **water** distribution, quality, and its relationship to geologic features), economic geology studies (where mines and excavations are studied and areas explored for the value of potential new mining), engineering geology field work (where studies assess the impact of human disturbance upon rock and **soil** stability), and many others.

See also Cartography; Topography and topographic maps

FISSION • *see* NUCLEAR FISSION

FISSURE

Any extensive crack in the earth is a fissure. When a small or medium-size fissure is filled with **magma** it is termed a **dike**. A large, magma-filled fissure that breaches the surface may erupt along its whole length or manifest as a chain of craters, each connected by a short central pipe to the magma-filled fissure below.

Small fissures are a common feature of volcanoes built by central activity (i.e., fed by a single pipelike conduit at their core). Indeed, most central volcanoes begin as eruptions from fissures and later localize to a single, central vent. High pressure in the central pipe may cause cracks in the surrounding cone or shield; if such a fissure breaches the surface, it may become a secondary point of eruption or even take over for the central crater. A fissure of this type typically appears at the surface as a hairline crack that gradually increases in width. Sulfurous fumes and steam emerge first, followed by small, glowing crumbs of red-hot **rock**. Later, viscous **lava** begins to bulge and ooze from the fissure, followed by increasingly fluid and voluminous flow. Not all fissures open so gradually; where magma meets subsurface **water**, steam explosions can open or widen a fissure suddenly.

Small fissures around central volcanoes are a parasitic phenomenon. In contrast, eruptions along large, independent fissures are a distinct type of volcanism. Such eruptions may be pyroclastic (i.e., explosive eruptions of solid fragments), such as that which covered the Valley of Ten Thousand Smokes in Alaska with some 1.7 mi^3 (7 km^3) of ash and **pumice** in 1912, or those which covered Nevada and western Utah with 12,000 mi^3 (50,000 km^3) of welded **tuff** in the early Oligocene and late Pliocene Epochs. Fissure eruptions may also be gradual, such as the Great Tolbachik Fissure Eruption on the Kamchatka Peninsula in Russia, that in 1975 vented lava from a fissure 19 mi (30 km) long for 450 days and covered more than 15 mi^2 (40 km^2) with lava flows.

Iceland is widening by about .5–1 in (1–2 cm) per year because it sits astride the Mid-Atlantic Ridge, and so is infiltrated by stretching-induced fissures that yield numerous fissure eruptions. Although not all independent fissure eruptions are on the largest scale, the most voluminous **volcanic eruptions** have all been fissure eruptions.

See also Crater, volcanic; Pipe, volcanic; Sea-floor spreading; Volcanic eruptions; Volcanic vent

FJORDS

Fjords (sometimes spelled fiords) are drowned glacier valleys. The depth of a fjord may exceed 1 mi (1.6 km) while the length sometimes exceeds 60 mi (97 km).

Geologic evidence indicates that some fjords form when a glacier cuts a deep, U-shaped valley through a river valley and advances into the sea. Given enough height and mass, the glacier may cut a valley into the sea floor as well. As it advances further into the sea, the glacier melts. The resulting reduction in size and mass causes the leading tongue of the glacier to float. A steep ridge is formed at the farthest reach of the glacier where the cutting stopped; this ridge is called a **sill**. In general, fjords can be identified by their steep sided, narrow channel, and sills.

Other evidence regarding the formation of fjords suggests that some of the deepest and most dramatic (such as those of Alaska, Norway, British Columbia, New Zealand, and other locations in the high latitudes) were formed during the most recent **ice** age. Evidence supports two scenarios to explain this process.

The first scenario suggests that some fjords resulted from landlocked **glaciers**. During the Ice Age, vast amounts of **water** were locked in enormous ice sheets. This reduced the availability of liquid water to Earth’s **oceans** and exposed miles of coastline. In the coldest latitudes, glaciers excavated valleys as they moved onto the newly exposed coastline without ever reaching the sea. With the coming of warmer climatic conditions, ice sheets began to melt, causing the oceans to rise. At the same time, glaciers on the dry coastal shelves retreated. As they retreated, the rising **seas** filled the U-shaped valleys left behind.

This water treatment plant in Des Moines, Iowa, was flooded by the Raccoon River in 1993. Flooding was a serious problem all over the United States that year due to rainfall amounts far above average. ***AP/Wide World. Reproduced by permission.***

The second scenario poses a combination of events that might account for the existence of some of the largest fjords. This explanation suggests that some glaciers did not remain land-locked on the coastal shelves during the ice age, but advanced for great distances and then continued their cutting on the sea floor. As the **climate** warmed, the rising seas occupied the deeply cut sea floor and advanced up the glacial valleys as the glaciers retreated.

It should be noted that fjords are classified as estuaries. However, due to their great depth and length, plus the height of their sills, they are semi-enclosed environments, similar to that of the open ocean. This characteristic sets fjords apart from all other estuarial environments.

See also Glacial landforms

FLOODPLAIN • *see* STREAM VALLEYS, CHANNELS, AND FLOODPLAINS

FLOODS

Floods can be defined as an overflow or downpour of **water** accumulating in an **area** where water is normally absent. Floods usually occur within a short period of time due to the soil's inability to absorb the water fast enough. According to the United States Geological Survey, floods were the natural disaster that caused the highest number of deaths and the most property damage in the United States during the twentieth century. Of all the natural disasters, floods are the most common and occur in the most places, with the only exception being fire. Flooding results in heavy currents that have the capacity to loosen structures and collapse foundations, destroying even the toughest of buildings.

The most common type of flood is the regional flood. Regional floods typically occur during the winter and spring months when the snow melts too rapidly or an excessive amount of water falls too quickly during spring rains or thunderstorms. Additionally, regional floods can result from tropical storms or hurricanes occurring along the coast or even far inland due to drastic changes in **weather** patterns. Floods can occur with no warning, but often occur over a period of days. If cold temperatures keep the ground frozen or the ground is already immersed with water, the water will run off into **rivers**. However, all too quickly the water rises above the banks of the rivers and flows onto dry land. Other types of floods include flash floods, ice-jam floods, storm-surge floods, dam-failure floods, and debris, **landslide**, and mudflow floods.

Regional floods across the U.S. that have occurred since 1990, include the Trinity, Arkansas, and Red Rivers in Texas, Arkansas, and Oklahoma in April of 1990, each caused by recurring thunderstorms. The number of reported deaths was 17 and the approximate cost of damage was one billion dollars. In January of 1993, the Gila, Salt, and Santa Cruz Rivers in Arizona flooded due to persistent winter **precipitation**, causing 400 million dollars in damages with the number of deaths unknown. From May through September of 1993, the Mississippi River Basin in the central U.S. flooded due to excessive rainfall, causing 48 deaths and 20 billion dollars in damages. In May 1995, flooding occurred in the south central U.S. from recurring thunderstorms causing 32 deaths and over five billion dollars in damages. Winter storms in California killed 27 people and caused three billion dollars in damages between January and May of 1995. Torrential rains and snowmelt caused flooding in the Pacific Northwest and western Montana in February of 1996 and again between December 1996, through January 1997. This caused nine deaths and one billion dollars in damages and 36 deaths and over two billion dollars in damages, respectively. The Ohio River and its tributaries flooded in March of 1997, causing more than 50 deaths and 500 million dollars in damages from a slow-moving frontal system. Snow **melting** caused the Red River of the North in North Dakota and Minnesota to flood between April and May of 1997, causing eight deaths and two billion dollars in damages. In September 1999, Hurricane Floyd destroyed eastern North Carolina, causing 42 deaths and six billion dollars in damages.

Flooding does not always prove destructive. Occasionally, floods can be beneficial, leaving **soil** laden with **minerals** and organic matter from the debris carried by the flood. Annual flooding of the Nile River enabled agriculture to be the foundation for Egyptian civilization. At the same time each year, the Nile River would flood, providing enough water to the soil to make lands fertile. With little rainfall, the Egyptians were dependent on the annual flooding to sustain their agriculture. Accordingly, Egypt's soil containing minerals and organic debris was a result of river sediment brought by the yearly floods.

See also Debris flow; Mud flow; Sedimentation

FOCUSED ION BEAM (FIB)

Focused ion beams have been used since the 1960s to investigate the chemical and isotopic composition of **minerals**. A focused ion beam blasts atoms and molecules free from the surface of a small sample of material; some of these free particles are also ions, and these are guided by electric fields to a mass spectrometer which identifies them with great precision.

An ion is an **atom** or molecule with a net electric charge. Electric fields subject electric charges to forces; therefore, electric fields can be used to move and steer ions. A continuous stream of ions moving together is termed an ion beam; a focused ion beam (FIB) is produced by using electric fields to guide a beam of ions.

In a typical FIB analysis, a narrow beam of argon, gallium, or **oxygen** ions traveling about 500,000 mph (800,000 kph) is directed at a polished flake of the material to be analyzed. Some of the atoms and molecules in the sample are kicked loose by the beam, a process termed sputtering. Some of these sputtered particles are themselves ions and so can be collected and focused by electric fields. The sputtered ions are directed to a mass spectrometer, which sorts them by mass. Even the very slight mass differences between isotopes of a single element can be distinguished by mass spectrometry; thus, not only the chemical but the isotopic composition of a sample can be determined with great precision. Very small, even microscopic, samples can be analyzed by FIB techniques.

The abundance of trace elements in a mineral can reveal information about the processes that formed it, helping petrologists and geochemists unravel geological history. Further, the decay of radioactive elements into isotopes of other elements acts as a built-in clock recording when the host mineral was formed. The hands of this clock are the relative isotope abundances in the mineral, and these can be determined by FIB analysis. **Carbon** isotope ratios also reveal whether a carbon-containing mineral was assembled by a living organism or by a nonliving process. Using FIB analysis, scientists have exploited this property of carbon isotopes to show that life existed on earth at least 3.85 billion years ago and that certain rocks originating on Mars and recovered as meteorites lying on the Antarctic **ice** probably, despite appearances, do not contain **fossils** of Martian microbes.

FIB facilities are complex and expensive. Accordingly, only about 15 facilities devoted to Earth sciences exist worldwide. FIBs are also used extensively in the manufacture of electronic microchips.

See also Carbon dating; Dating methods; Radioactivity

FOG

If the atmospheric visibility near the earth's surface is reduced to 0.62 mi (1 km) or less due to floating **water** droplets in the air, it is called fog. Fog can form in two ways: either by cooling the air to its **dew point** (e.g., radiation fog, **advection** fog, upslope fog), or by **evaporation** and mixing, when moisture is added to the air by evaporation, and then it is mixed with drier air (e.g., evaporation fog, frontal fog). Other types of fog include **ice** fog (a fog of suspended ice **crystals**, frequently forming in Arctic locations), acid fog (fog forming in polluted air, and turning acidic due to oxides of sulfur or nitrogen), or **smog** (fog consisting of water and smoke particles). While any type of fog can be hazardous because of its effects on atmospheric visibility for ground and air transportation, acid fog and smog can pose additional risk to human health, causing eye irritations or respiratory problems.

Radiation fog (or ground fog) occurs at night, when radiational cooling of the earth's surface cools the shallow moist air layer near the ground to its dew point or below, so the moisture in the air condenses into fog droplets. It occurs under calm **weather** conditions, when light **wind**, or no wind at all is present, since a strong wind would mix the lower-level cold air with the higher-level dry air, thus preventing the air at the bottom from becoming saturated enough to create fog. The presence of **clouds** at night can also prevent fog formation of this type, because they trap the earth's heat, not allowing the cooling of the air for **condensation**. Radiation fog often forms in late fall and winter nights, especially in lower areas, because cold and heavy air moves downhill, and gathers in valleys. Accordingly, radiation fog is also called valley fog. In the morning it usually dissipates or "burns off" when the Sun's heat warms the ground and air.

Advection fog forms when warm, moist air horizontally moves (which is called advection) over a cold surface, which cools the air to its dew point. Advection fog can form any time, and can be very persistent. It is common along coastlines where moist air moves from over the water to over the land, or when an air mass moves over a cold surface (e.g., snow), and the moisture in the air condenses into fog as the surface cools it. Advection-radiation fog forms when warm, moist air moves over a cold surface, which is cold as a result of radiation cooling. When warm, humid air moves over cold water, it is called sea fog.

Upslope fog forms in higher areas, where a moist air mass is forced to move up along a mountain. While the air mass is moving up the slope, it is cooled beyond its dew point and produces fog. It requires a fast wind, and warm and humid conditions at the surface. Unlike radiation fog, this type of fog dissipates when no more wind is available, and it can also form under cloudy skies. Upslope fog is usually dense, and extends to high altitudes.

Evaporation fog forms by the mixing of two unsaturated air masses. Steam fog is a type of evaporation fog, which appears when cold, dry air moves over warm water or warm, moist land. When some of the water evaporates into low air layers, and the warm water warms the air, the air rises, mixes with colder air, cools, and condenses some of its water vapor. Over **oceans**, it is referred to as sea smoke. Examples of cold air over warm water occur over swimming pools or hot tubs, where steam fog easily forms. It is common, especially in the fall season, when winds are getting colder but the water is only slowly turning colder.

Precipitation fog is a type of evaporation fog that happens when relatively warm rain or snow falls through cool, almost saturated air, and evaporation from the precipitation saturates the cool air. It can turn dense, persist for a long time, and may extend over large areas. Although it is mostly associated with warm fronts, it can occur with slow cold fronts or stationary fronts as well, hence the name frontal fog is also used.

See also Hydrologic cycle

FOHN • *see* SEASONAL WINDS

FOLDS

Compositional or metamorphic layers of rocks may bend during ductile deformation to produce folds. Folds commonly form during regional horizontal shortening in orogenic (mountain building) belts at microscopic to regional scales in all **rock** types (given suitable deformation conditions). Even rocks that at Earth's surface may be brittle and shatter when rapidly deformed, may fold during the application of regional, tectonic stresses over a long period of time at depth. Such a change in rock rheology is due to elevated **temperature** and confining pressure and the presence of fluids at deeper levels of the **crust**.

Upright layers (where young beds overlie older beds) that are arched upward are called anticlines. If the direction of younging (facing) is not known, such folds are called antiforms. Layers that are bent downward are called synclines (where beds are upright) or synforms where facing is not known. Cylindrical folds show the same profile in sections normal to their axes at any position along the axis. Folds where profiles vary from section to section and layers describe part of a cone are called conical folds. Folds are also classified according to the orientation of their hinge line or fold axis (the axis of curvature) and of their axial surface (the surface that bisects fold limbs and passes through the fold axis). The angle the fold hinge makes with the horizontal is called the plunge of a fold. Folds plunge gently when this angle is 10–30°, moderately between 30–60°, steeply between 60–90°, and are vertical when axes plunge 90°. Folds are upright where the axial surface is steeply dipping, inclined where the axial surface is moderately dipping, overturned where the axial surface is shallowly dipping and one limb is inverted, and recumbent where the axial surface is horizontal. In parallel folds, the layer thickness measured normal to the layer is constant around the fold. In similar folds, layer thicknesses measured parallel to the axial plane are constant. In describing folds, it is also important to note the inter-limb angle and whether fold hinges are rounded or angular.

Strong (competent) layers interlayered with more ductile (incompetent) layers buckle during layer-parallel shortening. The wavelength of the resulting folds depends on both the layer thickness and the viscosity (competence) contrast between layers. Larger wavelength folds develop in thick or competent layers. Folds may also develop during ductile flow in high-grade metamorphic rocks and in incompetent, lower-grade rocks. Irregular and often highly contorted syn-sedimentary folds can form during deposition of **sedimentary rocks** within slumps (which may be triggered by earthquakes).

When rocks that have already been folded are subjected to further shortening, early-formed folds may be refolded. Different fold interference patterns develop depending on the relative orientations of axes and axial surfaces for both generations of folds. A "dome and basin" (or, "egg carton") pattern results from the interference between two sets of upright folds whose axial surfaces are at a large angle to each other. A mushroom-shaped interference pattern results where folds with horizontal or shallowly dipping axial surfaces are folded by upright folds. A "hook" interference pattern occurs where fold axes are of similar orientation, but where axial surfaces are at a high angle to each other.

Folds may also form during regional crustal extension, such as in sedimentary basins. Roll-over antiforms develop over curved extensional (normal) faults in the upper, brittle crust or ductile **shear zones** in the middle to lower crust. Synforms are formed above areas where the underlying fault or ductile shear zone changes from shallowly to steeply dipping. Folds may also form during back-rotation of layers between two extensional faults or ductile shear zones. In high-grade rocks, folds may also form in surrounding layers when a competent layer pinches and swells or separates into barrel-shaped fragments (boudins) during layer-parallel extension.

Folds control the formation and localization of some **petroleum** and mineral deposits. Many oil and gas traps are created by regional-scale antiforms or domes formed by fold **superposition**, in wrench zones, or on the margins of salt diapirs. Some gold deposits are also controlled by folds. Differences in fold style of adjacent beds may lead to parting of beds along fold hinges. **Quartz** and, if chemical conditions are favorable, gold, may be deposited from fluids that migrate to such dilatational sites forming saddle reefs. In higher-grade rocks, rare metal pegmatites may intrude dilatational sites along fold hinges. Folds also provide geologists with valuable information about the orientation of stresses in Earth's crust at the time of their formation, helping them to unravel regional geological history.

See also Industrial minerals; Orogeny; Plate tectonics

FORAMINIFERAL OOZE • *see* CALCAREOUS OOZE

FORESTS AND DEFORESTATION

A forest is any ecological community that is structurally dominated by tree-sized woody plants. Forests occur anywhere that the **climate** is suitable in terms of length of the growing season, air and **soil temperature**, and sufficiency of soil moisture. Forests can be classified into broad types on the basis of their geographic range and dominant types of trees. The most extensive of these types are boreal coniferous, temperate angiosperm, and tropical angiosperm forests. However, there are regional and local variants of all of these kinds of forests. Old-growth tropical rainforests support an enormous diversity of species under relatively benign climatic conditions, and this ecosystem is considered to represent the acme of Earth's ecological development. Within the constraints of their regional climate, temperate and boreal forests also represent peaks of ecological development.

Many countries have developed national schemes for an ecological classification of their forests. Typically, these schemes are based on biophysical information and reflect the natural, large-scale patterns of species composition, soil type, **topography**, and climate. However, these classifications may vary greatly among countries, even for similar forest types.

An international system of ecosystem classification has been proposed by a scientific working group under the auspices of the United Nations Educational, Scientific and Cultural Organization (UNESCO). This scheme lists 24 forest types, divided into two broad classes: closed-canopy forests with a canopy at least 16.5 ft (5 m) high and with interlocking tree crowns, and open woodlands with a relatively sparse, shorter canopy.

Forests are among the most productive of Earth's natural ecosystems. Mature forests store more **carbon** (in biomass) than any other kind of ecosystem. This is especially true of old-growth forests, which typically contain large trees and, in temperate regions, a great deal of dead organic matter. Because all of the organic carbon stored in forests was absorbed from the atmosphere as **carbon dioxide** (CO_2), these ecosystems are clearly important in removing this greenhouse gas from the atmosphere. Conversely, the conversion of forests to any other type of ecosystem, such as agricultural or urbanized lands, results in a large difference in the amount of carbon stored on the site. That difference is made up by a large flux of CO_2 to the atmosphere. In fact, deforestation has been responsible for about one-half of the CO_2 emitted to the atmosphere as a result of human activities since the beginning of the industrial revolution.

Because they sustain a large biomass of foliage, forests evaporate large quantities of **water** to the atmosphere, in a hydrologic process called evapotranspiration. Averaged over the year, temperate forests typically evapotranspire 10–40% of their input of water by **precipitation**. However, this process is most vigorous during the growing season, when air temperature is highest and the amount of plant foliage is at a maximum. In fact, in many temperate forests evapotranspiration rates during the summer are larger than precipitation inputs, so that the ground is mined of its water content, and in some cases streams dry up.

Intact forests are important in retaining soil on the land, and they have much smaller rates of **erosion** than recently harvested forests or deforested landscapes. Soil eroded from disturbed forests is typically deposited into surface waters such as streams and **lakes**, in a process called **sedimentation**. The resulting shallower water depths makes flowing waters more prone to spilling over the banks of **rivers** and streams, causing flooding.

Forests are also important in moderating the peaks of water flow from landscapes, both seasonally and during extreme precipitation events. When this function is degraded by deforestation, the risk of flooding is further increased.

Although trees are the largest, most productive organisms in forests, the forest ecosystem is much more than a population of trees growing on the land. Forests also provide habitat for a host of other species of plants, along with numerous animals and microorganisms. Most of these associated species cannot live anywhere else; they have an absolute requirement of forested habitat. Often that need is very specific, as when a bird species needs a particular type of forest, in terms of tree species, age, and other conditions.

Generally, forests provide the essential habitat for most of Earth's species of plants, animals, and microorganisms. This is especially true of tropical rain forests. Recent reductions of forest **area**, which since the 1950s have mostly been associated with the conversion of tropical forest into agricultural land-use, are a critical environmental problem in terms of losses of biodiversity. Deforestation also has important implications for climate change and access to natural resources.

Forests are an extremely important natural resource that can potentially be repeatedly harvested and managed to yield a diversity of commodities of economic importance. Wood is by far the most important product harvested from forests. The wood is commonly manufactured into paper, lumber, plywood, and other products. In addition, in most of the forested regions of the less-developed world firewood is the most important source of energy used for cooking and other purposes. Potentially, all of these forest products can be sustained indefinitely. Unfortunately, in most cases forests have been irresponsibly over-harvested, resulting in the "mining" of the forest resource and widespread ecological degradation. It is critical that in the future all forest harvesting is conducted in a manner that is more responsible in terms of sustaining the resource.

Many other plant products can also be collected from forests, such as fruits, nuts, mushrooms, and latex for manufacturing rubber. In addition, many species of animals are hunted in forests, for recreation or for subsistence. Forests provide additional goods and services that are important to both human welfare and to ecological integrity, including the control of erosion and water flows, and the cleansing of air and water of pollutants. These are all important forest values, although their importance is not necessarily assessed in terms of dollars. Moreover, many of these values are provided especially well by old-growth forests, which in general are not very compatible with industrial forestry practices. This is one of the reasons why the conservation of old-growth forest is such a controversial topic in many regions of **North America** and elsewhere. In any event, it is clear that when forests are lost or degraded, so are these important goods and services that they can provide.

The global area of forest of all kinds was about 8.4 billion acres (3.4 billion ha) in 1990, of which 4.3 billion acres (1.76 billion ha) were tropical forest and the rest temperate and boreal forest. That global forest area is at least one-third smaller than it was prior to extensive deforestation caused by human activities. Most of the deforested land has been converted to permanent agricultural use, but some has been ecologically degraded into semi-desert or **desert**. This global deforestation, which is continuing apace, is one of the most serious aspects of the environmental crisis.

Deforestation refers to a longer-term conversion of forest to some other kind of ecosystem, such as agricultural or urbanized land. Sometimes, however, the term is used in reference to any situation in which forests are disturbed, for example by clear-cut harvesting, even if another forest subsequently regenerates on the site. Various human activities result in net losses of forest area and therefore contribute to deforestation. The most important causes of deforestation are the creation of new agricultural land and unsustainable harvesting of trees. In recent decades, deforestation has been proceeding most rapidly in underdeveloped countries of the tropics and subtropics.

The most important ecological consequences of deforestation are: the depletion of the economically important forest resource; losses of biodiversity through the clearing of tropical forests; and emissions of carbon dioxide with potential effects on global climate through an enhancement of Earth's **greenhouse effect**. In some cases, indigenous cultures living in the original forest may be displaced by the destruction of their habitat.

There are numerous references in historical, religious, and anthropological literature to forests that became degraded and were then lost through over harvesting and conversion. For example, the cedars of Lebanon were renowned for their abundance, size, and quality for the construction of buildings and ships, but today they only survive in a few endangered groves of small trees. Much of the deforestation of the Middle East occurred thousands of years ago. However, even during the Crusades of the eleventh century through the thirteenth century, extensive pine forests stretched between Jerusalem and Bethlehem, and some parts of Lebanon had cedar-dominated forests into the nineteenth century. These are all now gone.

Similar patterns of deforestation have occurred in many regions of the world, including most of the Mediterranean area, much of **Europe**, south **Asia**, much of temperate North and **South America**, and, increasingly, many parts of the subtropical and tropical world.

In recent decades, the dynamics of deforestation have changed greatly. The forest cover in wealthier countries of higher latitudes has been relatively stable. In fact, regions of Western Europe, the United States, and Canada have experienced an increase in their forest cover as large areas of poorer-quality agricultural land have been abandoned and then regenerated to forest. Although these temperate regions support large forest industries, post-harvest regeneration generally results in new forests, so that ecological conversions to agriculture and other non-forested ecosystems do not generally occur.

In contrast, the rate of deforestation in tropical regions of Latin America, **Africa**, and Asia has increased alarmingly in recent decades. This deforestation is driven by the rapid growth in size of the human population of these regions, with the attendant needs to create more agricultural land to provide additional food, and to harvest forest biomass as fuel. In addition, increasing globalization of the trading economy has caused large areas of tropical forest to be converted to agriculture to grow crops for an export market in wealthier countries, often to the detriment of local people.

In 1990, the global area of forest was 4.23 billion acres (1.71 billion ha), equivalent to 91% of the forest area existing in 1980. This represents an annual rate of change of about -0.9% per year, which if projected into the future would result in the loss of another one-half of Earth's remaining forest in only 78 years. During this period of time, deforestation (indicated as % loss per year) has been most rapid in tropical regions, especially West Africa (2.1%), Central America and Mexico (1.8%), and Southeast Asia (1.6%). Among nations, the most rapid rates of deforestation are: Côte d'Ivoire (5.2%/year), Nepal (4.0%), Haiti (3.7%), Costa Rica (3.6%), Sri Lanka (3.5%), Malawi (3.5%), El Salvador (3.2%), Jamaica (3.0%), Nicaragua (2.7%), Nigeria (2.7%), and Ecuador (2.3%).

These are extremely rapid rates of national deforestation. A rate of forest loss of 2% per year translates into a loss of one-half of the woodland area in only 35 years, while at 3% per year, the **half-life** is 23 years, and at 4%, it is 18 years.

Potentially, forests are a renewable natural resource that can be continually harvested to gain a number of economically important products, including lumber, pulp for the manufacture of paper, and fuel wood to produce energy. Forests also provide a habitat for game species and also for the much greater diversity of animals that are not hunted for sport or food. In addition, forests sustain important ecological services related to clean air and water and the control of erosion.

Any loss of forest area detracts from these important benefits and represents the depletion of an important natural resource. Forest harvesting and management can be conducted in ways that encourage the regeneration of another forest after a period of recovery. However, this does not happen in the cases of agricultural conversion and some types of unsustainable forest harvesting. In such cases, the forest is "mined" rather than treated as a renewable natural resource, and its area is diminished.

At the present time, most of Earth's deforestation involves the loss of tropical forests, which are extremely rich in species. Many of the species known to occur in tropical forests have local (or endemic) distributions, so they are vulnerable to extinction if their habitat is lost. In addition, tropical forests are thought to contain millions of additional species of plants, animals, and microorganisms as yet undiscovered by scientists.

Tropical deforestation is mostly caused by various sorts of conversions, especially to subsistence agriculture, and to market agriculture for the production of export commodities. Tropical deforestation is also caused by unsustainable logging and fuel wood harvesting (about two thirds of tropical people use wood **fuels** as their major source of energy. Less important causes of tropical deforestation include hydroelectric developments that flood large reservoirs and the production of charcoal as an industrial fuel. Because these extensive conversions cause the extinction of innumerable species, tropical deforestation is the major cause of global biodiversity concern.

Mature forests contain large quantities of organic carbon, present in the living and dead biomass of plants, and in organic matter of the forest floor and soil. The quantity of carbon in mature forests is much larger than in younger, successional forests, or in any other type of ecosystem, including human agroecosystems. Therefore, whenever a mature forest is disturbed or cleared for any purpose, it is replaced by an ecosystem containing a much smaller quantity of carbon. The difference in carbon content of the ecosystem is balanced by an emission of carbon dioxide (CO_2) to the atmosphere. This CO_2 emission always occurs, but its rate can vary. The CO_2 emission is relatively rapid, for example, if the biomass is burned, or much slower if resulting timber is used for many years and then disposed into an anaerobic landfill, where biological decomposition is very slow.

Prior to any substantial deforestation caused by human activities, Earth's vegetation stored an estimated 990 billion tons (900 billion metric tons) of carbon, of which 90% occurred in forests. Mostly because of deforestation, only about 616 billion tons (560 billion metric tons) of carbon are presently stored in Earth's vegetation, and that quantity is diminishing further with time. It has been estimated that between 1850 and 1980, CO_2 emissions associated with deforestation were approximately equal to emissions associated with the combustion of fossil fuels. Although CO_2 emissions from the use of fossil fuels has been predominant in recent decades, continuing deforestation is an important source of releases of CO_2 to the atmosphere.

The CO_2 concentration in Earth's atmosphere has increased from about 270 ppm prior to about 1850, to about 360 ppm in 1999, and it continues to increase. Many atmospheric scientists hypothesize that these larger concentrations of atmospheric CO_2 will cause an increasing intensity of an important process, known as the greenhouse effect, that interferes with the rate at which Earth cools itself of absorbed solar radiation. If this theory proves to be correct, then a climatic warming could result, which would have enormous implications for agriculture, natural ecosystems, and human civilization.

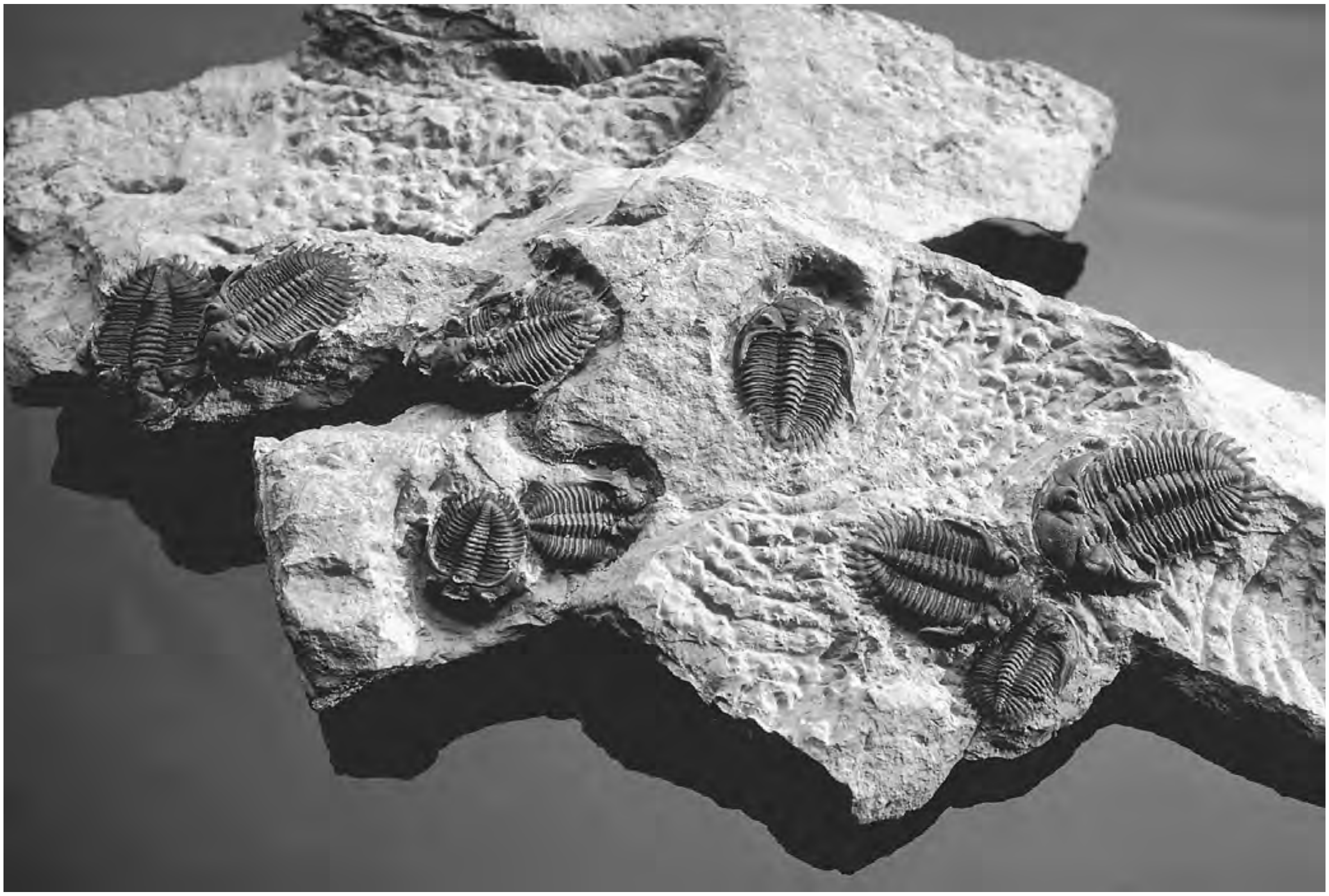
See also Acid rain; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Exfoliation; Floods; Global warming; Greenhouse gases and greenhouse effect; History of exploration I (Ancient and classical); History of exploration II (Age of exploration)

FOSSIL FUELS • *see* PETROLEUM

FOSSIL RECORD

The fossil record is the record of life on Earth as it is preserved in **rock** as **fossils**. The fossil record provides evidence of when and how life began on the planet, what types of organisms existed and how long they persisted, how they lived, died, and evolved, and what the **climate** was and how it changed. The fossil record also has allowed scientists to correlate rocks on a worldwide basis and to determine the relative ages of rock formations.

Fossils record life by preserving remains of organisms. A fossil is a rare thing. Most organisms decay and disappear quickly after dying. Of the tiny minority of organisms that do become preserved as fossils, an even smaller fraction survives the geologic cycle to become exposed and visible. As a result the fossil record is incomplete; there is no record of most organisms that probably lived and died.



Trilobite fossils. *© James L. Amos/Corbis. Reproduced by permission.*

The interpretation of the fossil record requires describing fossils, classifying them to place them in a biological context, and determining their age to give them chronological context. Fossil classification follows the same system of taxonomy as modern biology. Fossil organisms are placed in a genus, species, etc. Owing to the incompleteness of the fossil record, the classification of fossil organisms includes only about 250,000 species, a small number when compared to the over 2 million species of modern organisms that have been identified.

The most direct information the fossil record provides is of an organism's physical structure and what it may have looked like, thereby enabling it to be classified. Other information such as its environment, its diet, and its life cycle is deduced from its physical attributes, from other fossils found in association, and from the types of rocks containing the fossils. Trace fossils, or fossilized marks left as a result of the activities of creatures such as trails, footprints, and burrows also provide important information.

Of critical importance to the fossil record is the age of fossils. Many theories about how Earth and life on it evolved would not be possible without knowing the time sequence of the fossil record. The age of fossils is determined by two methods: relative dating and absolute dating. Relative dating involves comparing one rock formation with another and deciding the relative ages of the two formations. For example, when one formation is found above another, the lower formation and the fossils it contains must have been deposited prior to the overlying formation and so must be older. This rule, known as the principle of **superposition**, holds as long as the rocks have not been overturned by faulting or folding. In determining an absolute age, radiometric age dating is used. This method measures the abundance of a radioactive element in a fossil or an associated rock. An absolute age is then reverse-calculated based on the rate of decay, or **half-life** of the element.

Often, certain fossils are found in a limited vertical sequence of rock and are assumed to represent a limited time period. These fossils, known as index fossils, are useful for determining relative ages and for correlating rock formations on a worldwide basis. Early workers used index fossils and rock **correlation** to develop the geologic scale. Originally, the geologic scale was relative, based largely on the fossil record. Subsequently, absolute ages have been applied to the geologic scale.

By synthesizing the fossil record, classifying fossils, aging them, and placing them in the context of the geologic scale, scientists have revealed the sequence of life on Earth. In many cases, the scale shows how some organisms evolved systematically over time, each subsequent version of an organism displaying modifications over the earlier. In other cases, there are large gaps in the fossil record and the developmental process for some organisms is not as clear. Often, the **evolution** of organisms leads to a dead end. The fossil record shows that throughout **geologic time**, life often evolved slowly, punctuated by explosions of life when a large number new organisms appeared. For example, the beginning of the **Cambrian Period** of the geologic scale contains a phenomenal number of new organisms. It also shows that, periodically, mass extinctions occurred, such as at the end of the **Cretaceous Period**, when a majority of species came to an end over a relatively short amount of time.

The fossil record begins with 3.5 to 3.0 billion-year-old rocks from **Australia** and South **Africa**, which preserve the remains of blue-green algae. These fossils resemble the modern stromatolites that grow in oceanic tidal areas. The fossil record shows a steady increase in the complexity of marine organisms over the next three billion years. Eventually, about 435 million years ago, terrestrial organisms appeared. The subsequent rise and fall of different creatures, from insects to fish, dinosaurs to mammals, has all been deduced from the fossil record.

In addition to outlining the history of life on Earth, the fossil record provides clues to climatic and tectonic evolution of the planet. Plant fossils and microscopic fossils such as pollen are particularly useful for the evidence they provide about the climate of the earth. For example, the Carboniferous period must have been very warm and moist because of the presence of abundant fossils of ferns and other tropical plants from that time. Also, the lack of fossilized remains of **oxygen** breathing organisms and the dominance of photosynthetic algae fossils from the very early Earth suggest that the primordial atmosphere was devoid of oxygen. The concept of **plate tectonics** was greatly aided by the observation that fossils now found widely spaced across the globe must have actually lived on the same original landmass that subsequently split apart.

See also Evolution, evidence of; Fossils and fossilization; Uniformitarianism

FOSSILIZATION OF BACTERIA

Studies of **fossilization** of bacteria provide an indication of the age of ancient bacteria and of the rate of geological and geochemical processes on ancient Earth. **Fossils** of cyanobacteria or “blue-green algae” have been recovered from rocks that are nearly 3.5 million years old. Bacteria known as magnetobacteria form very small **crystals** of a magnetic compound inside the cells. These crystals have been found inside **rock** that is two billion years old.

The fossilization process in cyanobacteria and other bacteria appears to depend on the ability of the bacteria to trap sediment and **metals** from the surrounding solution. Cyanobacteria tend to grow as mats in their aquatic environment. The mats can retain sediment. Over time and under pressure the sediment entraps the bacteria in rock. As with other living organisms, the internal structure of such bacteria is replaced by **minerals**, notably pyrite or siderite (**iron** carbonate). The result, after thousands to millions of years, is a replica of the once-living cell.

Other bacteria that elaborate a carbohydrate network around themselves also can become fossilized. The evidence for this type of fossilization rests with laboratory experiments where bacteria are incubated in a metal-containing solution under conditions of **temperature** and pressure that attempt to mimic the forces found in geological formations. Experiments with *Bacillus subtilis* demonstrated that the bacteria act as a site of **precipitation** for silica, the ferric form of iron, and of elemental gold. The binding of some of the metal ions to available sites within the carbohydrate network then acts to drive the precipitation of unstable metals out of solution and onto the previously deposited metal. The resulting cascade of precipitation can encase the entire bacterium in metallic species. On primordial Earth, this metal binding may have been the beginning of the fossilization process.

The deposition of metals inside carbohydrate networks like the capsule or exopolysaccharide surrounding bacteria is a normal feature of bacterial growth. Indeed, metal deposition can change the three-dimensional arrangement of the carbohydrate strands so as to make the penetration of antibacterial agents through the matrix more difficult. In an environment—such as occurs in the lungs of a cystic fibrosis patient—this micro-fossilization of bacteria confers a survival advantage to the cells.

In contrast to fossils of organisms such as dinosaurs, the preservation of internal detail of microorganisms seldom occurs. Prokaryotes have little internal structure to preserve. However, the mere presence of the microfossils is valuable, as they can indicate the presence of microbial life at that point in geological time.

Bacteria have been fossilized in amber, which is fossilized tree resin. Several reports have described the resuscitation of bacteria recovered from amber as well as bacteria recovered from a crystal in rock that is millions of years old. Although these claims have been disputed, a number of microbiologists assert that the care exercised by the experimenters lends increases the validity of their studies.

In the late 1990s a meteorite from the planet Mars was shown to contain bodies that appeared very similar to bacterial fossils that have been found in rocks on Earth. Since then, further studies have indicated that the bodies may have arisen by inorganic (non-living) processes. Nonetheless, the possibility that these bodies are the first extraterrestrial bacterial fossils has not been definitively ruled out.

See also Atmospheric chemistry; Carbon dating; Dating methods; Evolution, evidence of; Fossil record; Fossils and fossilization; Geochemistry; Miller-Urey experiment; Murchison meteorite; Paleoclimate; Petroleum microbiology; Phanerozoic Eon; Precambrian; Rate factors in geologic processes

FOSSILS AND FOSSILIZATION

A fossil is the remains of an ancient life form—plant or animal—or its traces, such as nesting grounds, footprints, worm trails, or the impressions left by leaves, preserved in **rock**. Fossil traces are called ichnofossils. Fossilization refers to the series of postmortem changes that lead to replacement of **minerals** in the original hard parts (shell, skeleton, teeth, horn, scale) with different minerals, a process known as remineralization. Infrequently, soft parts may also be mineralized and preserved as fossils. A new category of subfossil—a fossil that has not yet begun to mineralize—is increasingly recognized in the scientific literature. Many subfossils originated in the Holocene or Recent, the period that we now live in, and cannot be dated with any greater accuracy. In addition, the term "fossil" is applied in other ways, for example, to preserved soils and landscapes such as fossil **dunes**. Through the study of fossils, it is possible to reconstruct ancient communities of living organisms and to trace the **evolution** of species.

Fossils occur on every continent and on the sea floors. The bulk of them are invertebrates with hard parts (for example, mussels). Vertebrates, the class that includes reptiles (for example, dinosaurs) and mammals (mastodons, humans), are a relatively late development, and the finding of a large, complete vertebrate fossil, with all its parts close together, is rare. Microfossils, on the other hand, are extremely common. The microfossils include very early bacteria and algae; the unicellular organisms called foraminiferans, which were common in the Tertiary Periods; and fossil pollen. The study of micro fossils is a specialized field called micropaleontology.

Fossils of single-celled organisms have been recovered from rocks as old as 3.5 billion years. Animal fossils first appear in late **Precambrian** rocks dating back about a billion years. The occurrence of fossils in unusual places, such as dinosaur fossils in **Antarctica** and fish fossils on the Siberian steppes, reflects both shifting of continental position by **plate tectonics** and environmental changes over time. The breakup of the supercontinent Pangaea in the **Triassic Period** pulled apart areas that were once contiguous and shared the same flora and fauna. In particular, the plates carrying the southern hemisphere continents—South America, southern **Africa**, the Indian subcontinent, **Australia**, and Antarctica—moved in different directions, isolating these areas. Terrestrial vertebrates were effectively marooned on large islands. Thus, the best explanation for dinosaurs on Antarctica is not that they evolved there, but that Antarctica was once part of a much larger land mass with which it shared many life forms.

An important environmental factor influencing the kinds of fossils deposited has been radical and episodic alteration in sea levels. During episodes of high sea level, the interiors of continents such as **North America** and Australia are flooded with seawater. These periods are known as marine transgressions. The converse, periods of low sea level when the waters drain from the continents, are known as marine regressions. During transgressions, fossils of marine animals may be laid down over older beds of terrestrial animal fossils. When sea level falls, exposing more land at the edges of continents, fossils of terrestrial animals may accumulate over older marine animals. In this way plate tectonics and the occasional marine flooding of inland areas could result in unusual collections of fossil flora and fauna where the living plants or animals could not exist today—such as fishes on the Siberian steppes.

Changes in sea level over the past million years or so have been related to episodes of **glaciation**. During glaciation, proportionately more **water** is bound up in the **polar ice** caps and less is available in the **seas**, making the sea levels lower. It is speculated, but not certain, that the link between glaciation and lower sea levels holds true for much of Earth's history. The periods of glaciation in turn are related to broad climatic changes that affect the entire Earth, with cooler **weather** increasing glaciation and with warmer temperatures causing glacial **melting** and a rise in sea levels. A change in **temperature** would also affect the availability of plants for herbivores to eat, and the availability of small animals for carnivores to eat. Thus, even modest temperature changes, if long-lasting enough, could produce large changes in the flora and fauna available to enter the **fossil record** in any given locale.

The principal use of fossils by geologists has been to date rock strata (layers) that have been deposited over millions of years. As different episodes in Earth's history are marked by different temperature, aridity, and other climatic factors, as well as different sea levels, different life forms were able to survive in one locale or period but not in another. Distinctive fossilized life forms that are typically associated with given intervals of **geologic time** are known as index fossils, or indicator species. The concepts that different fossil species correlate with different strata and that, in the absence of upheaval, older strata underlie younger ones are attributed to the English geologist **William Smith**, who worked in the early nineteenth century.

The temporal relationship of the strata is relative: it is more important to know whether one event occurred before, during, or after another event than to know exactly when it occurred. Recently geologists have been able to subdivide time periods into smaller episodes called zones, based on the occurrence of characteristic zonal indicator species, with the smallest time slices about one-half million years. Radiometric dating measures that measure the decay of radioactive isotopes have also been used to derive the actual rather than relative dates of geological periods; the dates shown on the time scale were determined by radiometry. The relative dating of the fossil clock and the quantitative dating of the radiometric clock are used in combination to date strata and geological events with good accuracy.

The fossil clock is divided into units by index fossils. Certain characteristics favor the use of one species over another as an index fossil. For example, the ammonoids (ammonites), an extinct mollusk, function as index fossils from the lower Devonian through the upper Cretaceous—a period of about 350 million years. The ammonoids, marine animals with coiled, partitioned shells, in the same class (Cephalopoda) as the present-day Nautilus, were particularly long lasting and plentiful. They evolved quickly and colonized most of the seas on the planet. Different species preferred warmer or colder water, evolved characteristically sculpted shells, and exhibited more or less coiling. With thousands of variations on a few basic, easily visible features—variations unique to each species in its own time and place—the ammonoids were obvious candidates to become index fossils. For unknown reasons, this group of immense longevity became extinct during the Cretaceous-Triassic mass extinction. The fossils are still quite plentiful; some are polished and sold as jewelry or paperweights.

Index fossils are used for relative dating, and the geologic scale of time is not fixed to any one system of fossils. Multiple systems may coexist side-by-side and be used for different purposes. For example, because macrofossils such as the ammonoids may break during the extraction of a core sample or may not be frequent enough to lie within the exact **area** sampled, a geologist may choose to use the extremely common microfossils as the indicator species. Workers in the oil industry may use conodonts, fossils commonly found in oil-bearing rocks. Regardless of which system of index fossils is used, the idea of relative dating by means of a fossil clock remains the same.

The likelihood that any living organism will become a fossil is quite low. The path from **biosphere** to lithosphere—from the organic, living world to the world of rock and mineral—is long and indirect. Individuals and even entire species may be snatched from the record at any point. If an individual is successfully fossilized and enters the **lithosphere**, ongoing tectonic activity may stretch, abrade, or pulverize the fossil to a fine dust, or the sedimentary layer housing the fossil may eventually be subjected to high temperatures in Earth’s interior and melt, or be weathered away at Earth’s surface. A fossil that has survived or avoided these events may succumb to improper collection techniques at the hands of a human.

Successful fossilization begins with the conditions of death in the biosphere. Fossils occur in sedimentary rock, and are incorporated as an integral part of the rock during rock formation. Unconsolidated sediments such as **sand** or mud, which will later become the fossiliferous (fossil-bearing) **sandstone** or **limestone**, or shale, are an ideal matrix for burial. The organism should also remain undisturbed in the initial phase of burial. Organisms exposed in upland habitats are scavenged and weathered before they have an opportunity for preservation, so a low-lying habitat is the best. Often this means a watery habitat. The fossil record is highly skewed in favor of organisms that died and were preserved in calm seas, estuaries, tidal flats, or the deep ocean floor (where there are few scavengers and little disruption of layers). Organisms that died at altitude, such as on a plateau or mountainside, and are swept by **rivers** into a **delta** or **estuary** may be added to this death assemblage, but are usually fragmented.

A second factor contributing to successful fossilization is the presence of hard parts. Soft-bodied organisms rarely make it into the fossil record, which is highly biased in favor of organisms with hard parts—skeletons, shells, woody parts, and the like. An exception is the Burgess Shale, in British Columbia, where a number of soft-bodied creatures were fossilized under highly favorable conditions. These creatures have few relatives that have been recorded in the fossil record; this is due to the unlikelihood of the soft animals being fossilized.

From the time of burial on, an organism is technically a fossil. Anything that happens to the organism after burial, or anything that happens to the sediments that contain it, is encompassed by the term diagenesis. What is commonly called fossilization is simply a postmortem alteration in the **mineralogy** and **chemistry** of the original living organism.

Fossilization involves replacement of minerals and chemicals by predictable chemical means. For example, the shells of mollusks are made of calcium carbonate, which typically remineralizes to calcite or aragonite. The bones of most vertebrates are made of calcium phosphate, which undergoes subtle changes that increase the phosphate content, while cement fills in the pores in the bones. These bones may also be replaced by silica.

Because of the nature of fossilization, fossils are often said to exist in communities. A fossil community is defined by **space**, not time. Previously fossilized specimens of great age may be swept by river action or carried by scavengers into young sediments that are just forming, there to join the fossil mix. For this reason, it may be very difficult to date a fossil with precision based on a presumed association with nearby fossils. Nevertheless, geologists do hope to confirm relationships among once living communities by comparing the makeup of fossil communities.

One of the larger goals of paleontologists is to reconstruct the prehistoric world, using the fossil record. Inferring an accurate life assemblage from a death assemblage is insufficient and usually wrong. The fossil record is known for its extreme biases. For example, in certain sea environments over 95% of species in life may be organisms that lack hard parts. Because such animals rarely fossilize, they may never show up in the fossil record for that locale. The species diversity that existed in life will therefore be much reduced in the fossil record, and the proportional representation of life forms greatly altered.

In some cases, however, a greater than usual proportion of preservable individuals in a community has fossilized in place. The result is a bed of fossils, named after the predominant fossil component, “bone bed” or ‘‘mussel bed,” for example. Geologists are divided over whether high-density fossil deposits are due to reworking and **condensation** of fossiliferous sediments or to mass mortality events. Mass mortality—the contemporaneous death of few to millions of individuals in a given area—usually is attributed to a natural catastrophe. In North America, natural catastrophe is thought to have caused the sudden death of the dinosaurs in the bone beds at Dinosaur National Park, Colorado, and of the fossil fishes in the Green River Formation, Wyoming. These are examples of local mass mortality. When mass mortality occurs on a global scale and terminates numerous species, it is known as a mass extinction. The greatest mass extinctions have been used to separate the geological eras: the Permian-Triassic extinction separates the Palaeozoic Era from the Mesozoic; the Cretaceous-Tertiary extinction, which saw the demise of the dinosaurs and the rise of large mammalian species to fill newly available biological niches, separates the Mesozoic from the Tertiary. Thus, mass extinctions are recorded not only in the high-density fossil beds but in the complete disappearance of many species from the fossil record.

The fossil record—the sum of all known fossils—has been extremely important in developing the phylogeny, or evolutionary relations, of ancient and living organisms. The contemporary understanding of a systematic, phylogenetic hierarchy descending through each of the five kingdoms of living organisms has replaced earlier concepts that grouped organisms by such features as similar appearance. It is now known that unrelated organisms can look alike and closely related organisms can look different; thus, terms like "similar" have no analytical power in biology. Charles Darwin, working in the mid-1800s, was the chief contributor to the systematic approach to biological relationships of organisms.

In addition to providing important information about the history of Earth, fossils have industrial uses. Fossil **fuels** (oil, **coal**, **petroleum**, bitumen, **natural gas**) drive industrialized economies. Fossil aggregates such as limestone provide building material. Fossils are also used for decorative purposes. This category of functional use should be distinguished from the tremendous impact fossils have had in supporting evolutionary theory.

See also Evolution, evidence of; Geologic time; Marine transgression and marine regression

FRACTIONAL CRYSTALIZATION • *see* CRYSTALS AND CRYSTALLOGRAPHY

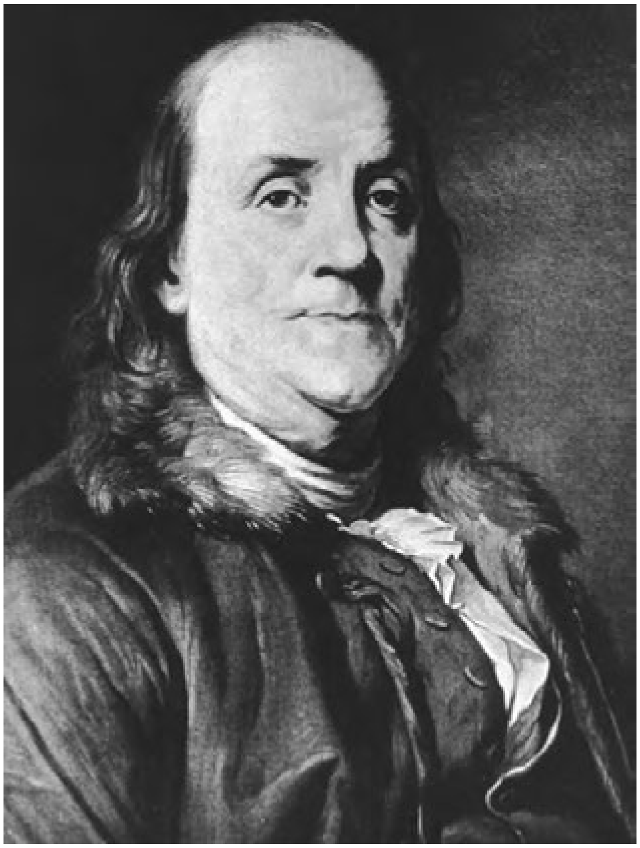
FRANKLIN, BENJAMIN (1706-1790)

American scientist and statesman

Before serving his fledgling country during time of revolution, Benjamin Franklin also achieved international recognition for his scientific acumen, especially in his experimentation with **electricity**.

Born in the British colony of Boston, Massachusetts, Franklin was the fifteenth of seventeen children. His father was an impoverished candlemaker, unable to afford to send young Benjamin to school. As a result, he received only two years of formal education. Franklin was working in his father's shop at the age of ten, and later was apprenticed to his brother, a printer, where he developed a love for books. In 1724, he went to London where he became skilled at printing, returning to Philadelphia two years later. In Philadelphia he made a name for himself, as well as a small fortune, publishing the *Pennsylvania Gazette* and *Poor Richard's Almanack.*

In addition to his pursuit of printing, Franklin became interested in the study of electricity in 1746. During this period, scientists around the globe, many of whom had advanced degrees, were investigating the phenomena of static electricity. A less confident man might have felt inadequate to compete, but Franklin, who was essentially self-educated, obtained a Leyden jar and began his own research.



Benjamin Franklin. ***Library of Congress.***

The Leyden jar, invented by Musschenbroek, was a water-filled bottle with a stopper in the end. Through the stopper was a metal rod that extended into the **water**. A machine was used to create a static electric charge, which could be stored in the jar. A person who touched the end of the charged rod received an electrical jolt. Public demonstrations, in which many people joined hands and received a simultaneous shock, were very popular. Franklin saw such a demonstration, and that initiated his interest in electricity.

It was Franklin's originality and tenacity that earned him the reputation as a leading scientist. He was the first person to wonder how the Leyden jar actually worked, and performed a series of experiments to find the answer. He poured the "charged" water out of the jar into another bottle, and discovered the water had lost its charge. This indicated that it was the **glass** itself, the material that insulated the conductor, which produced the shock. To verify this, Franklin took a windowpane and placed a sheet of **lead** on each side. He "electrified" the lead, removed each sheet one at a time, and tested for a charge. Neither sheet gave so much as a single spark, but the windowpane had been charged. Franklin had unknowingly invented the electrical condenser. The condenser, also known as a capacitor, was destined to be one of the most important elements in electric circuits. Today the condenser, which received its name from Alessandro Volta, is used in radios, televisions, telephones, radar systems, and many other devices.

Drawing a parallel between the sparking and crackling of the charged Leyden jar and **lightning** and **thunder**, Franklin wondered if there was an electrical charge in the sky. He planned to erect a long metal rod atop Christ Church in Philadelphia to conduct electricity to a sentry box in which a man, standing on an insulated platform, would be able to collect an electric charge. Because he was a proponent in the free exchange of ideas, Franklin had written a book outlining his theories, which received wide circulation in **Europe**. A French scientist named D'Alibard used Franklin's idea and performed the experiment himself on May 10, 1752, charging a Leyden jar with lightning. Franklin generously gave D'Alibard credit for being the first to "draw lightning from the skies." If nothing else, Franklin did receive credit for the invention of the lightning rod.

While waiting for the rod to be installed atop Christ Church, Franklin had come up with an idea of a faster way to get a conductor into the sky. He tied a large silk handkerchief to two crossed wooden sticks, attached a long silken thread with a metal key at the end, and waited for a thunderstorm. The rain made the thread an excellent conductor, and the static charge traveled down to the key. When Franklin brought his knuckle to the key, a spark jumped from the key to his hand, proving the existence of electricity in the sky.

Franklin had been wise enough to connect a ground wire to his key; two other scientists, attempting to duplicate the experiment but neglecting the ground wire, were killed when they were actually struck by lightning. Still, Franklin was lucky he was not hit by lightning himself. Franklin invented the lightning rod from his work with electricity. The lightning rod became indispensable for protecting buildings from the destructive force of lightning. Because he had discovered he could get the Leyden jar to spark over a greater distance with a sharply pointed rod, Franklin's lightning rods had very sharp points. (In 1776, after the conflict between the Colonies and King George III had erupted, the king ordered that lightning rods with blunt ends be installed on his palace.) By 1782, there were four hundred lightning rods in Philadelphia.

His discovery of sky-borne electricity led Franklin to speculate on the nature of the **aurora borealis**, the "northern lights" that illuminate the sky. Franklin thought they might be electrical in nature, and suggested that conditions in the upper atmosphere might be responsible.

His work on electricity led to a plethora of new words (battery, condenser, conductor, armature, charge, and discharge to name a few) and concepts. He suggested that electrical charge was due to the abundance or lack of "something" that resulted in attraction and repulsion, and he established the concept of positive and negative charges, believing (incorrectly) that electrical flow went from positive to negative. In fact, the opposite is true.

Continuing his observations of the **weather**, he noticed there was a prevailing pattern as it moved from west to east and suggested the circulation of air masses was responsible, establishing the concept of high and low pressure. He went on to show that the boiling point of water was affected by air pressure; as he created a vacuum in a sealed water bottle, the **temperature** needed to boil the water dropped. He also charted the flow on the **Gulf Stream** in the Atlantic Ocean.

Volumes have been written about Franklin's life as a statesman. He founded service organizations, became Postmaster of Philadelphia, and established a college that eventually became the University of Pennsylvania. He returned to London in 1757 as an Agent of the Pennsylvania Assembly and remained there until 1775. After warning that the "Stamp Tax" was not a good way to obtain revenue from the American Colonies, he returned and joined the committee drafting the Declaration of Independence.

During Franklin's long life he developed many inventions (such as bifocal lenses and the Franklin stove), received numerous honors and achieved an international reputation, becoming one of few Americans of colonial days to do so. He died in Philadelphia, at the age of eighty-four.

See also Atmospheric pressure; Electricity and magnetism

FRASCH, HERMAN (1851-1914)

German-born American chemist

Herman Frasch, the son of a prosperous apothecary, was born in Gaildorf, Württemberg (now part of Germany) on Christmas Day 1851. He studied at the gymnasium in Halle but rather than attend the university, he decided to immigrate to the United States in 1868. Frasch taught at the Philadelphia College of Pharmacy and continued to study **chemistry** with an eye to becoming an expert in a newly-emerging field, **petroleum**.

The oil industry in the United States began with the opening of the Titusville, Pennsylvania, oil field in 1859. In 1870, John D. Rockefeller formed Standard Oil—which refined a majority of the oil in the country—in Cleveland, Ohio. Frasch sold his patent for an improved process for refining paraffin wax to a subsidiary of Standard Oil in 1877 and moved to Cleveland to open a laboratory and consulting office. Soon he became the city's outstanding chemical consultant. In 1882, he sold to the Imperial Oil Company in Ontario, Canada, a process for reducing the high sulfur content of petroleum, which gave it a disagreeable odor and caused the kerosene refined from it to burn poorly. When Standard Oil discovered a field of "sour oil" in Indiana and Ohio, the company hired Frasch as a full time consultant, bought his process and the Empire Oil Company he had recently purchased in Ontario, and gave him charge of the American petroleum industry's first experimental research program. Frasch's process for removing sulfur, patented in 1887, was to treat the petroleum with a variety of metallic oxides to precipitate the sulfur and recover the oxides for further use. He continued with Standard Oil as special consultant for the development of new petroleum by-products and became wealthy. He refused to join Standard Oil as an executive, choosing instead to be a lifetime consultant.

Frasch turned his attention to sulfur, the substance his process removed from petroleum. The island of Sicily held a virtual monopoly on this valuable mineral from which sulfuric acid, industry's most vital chemical, was made. While Sicilian sulfur deposits were near the earth's surface and more easily mined, sulfur deposits in Texas and Louisiana were deeper, and American laborers were unwilling to go into sulfur mines. Frasch believed that sulfur could be melted and pumped from the ground in much the same manner petroleum was, but boiling **water** was not hot enough to liquefy the sulfur. He organized the Union Sulfur Company in 1892, and two years later began employing the method he had patented a year earlier. His process required three concentric pipes to be sunk into the sulfur deposit. Water, superheated under pressure to above 241°F (116°C), was pumped into the sulfur deposit through the outside pipe. Compressed air was forced down the center pipe, and through the center pipe the melted sulfur flowed to the surface where it was pumped into bins to solidify. The major problem with this method was the cost of heating the water, but the discovery of the East Texas oil fields in the early twentieth century provided an inexpensive, readily available fuel supply. Frasch expanded his research into the use of sulfur as an insecticide and a fungicide. Other companies infringed on his patent rights, and his company disappeared, but the use of the Frasch process enabled the United States to become self-sufficient in the production of sulfur needed to supply its growing chemical industry.

Frasch died in Paris on May 1, 1914. Among his honors was the Perkin Medal in 1912. His greatest honor was the distinction of having two chemical processes, one for producing sulfur and the other for removing sulfur from petroleum, carry his name.

See also Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration

FREEZING AND MELTING

Freezing is the change that occurs when a liquid changes into a solid as the **temperature** decreases. Melting is the opposite change, from a solid to a liquid as the temperature increases. These are both examples of changes in the states of matter of substances.

Substances freeze at exactly the same temperature as they melt. As a consequence, the temperature at which—under a specified pressure—liquid and solid exist in equilibrium is defined as the melting or freezing point. When the pressure is one atmosphere, this temperature is known as the normal freezing (or melting) point. A change in pressure will change the temperature at which the change in the state of matter occurs. A decrease in pressure will decrease the temperature at which this occurs and an increase in pressure will increase the temperature required.

At a fundamental level freezing and melting represent changes in the energy levels of the molecules of the substance under consideration. Freezing is a change from a high energy state to one of lower energy, the molecules are moving less as their temperature falls. They become more ordered and fixed in shape. When a substance melts the average energy level of the constituent molecules increases. The molecules are moving more rapidly and in a less ordered manner in a liquid than in a solid. It is this greater freedom of movement that allows a liquid to flow to touch the walls of its container whereas a solid is fixed in a rigid shape. This consideration of the energy of the molecules is known as the kinetic molecular theory.

The temperature at which substances freeze and melt is different for different chemicals. The chemical formula of a substance is not necessarily a true indicator of what the freezing or melting point may be. Isomers of substances can have different physical properties including freezing and melting points. Similarly the presence of hydrogen bonds and other attractive forces such as van der Waals forces can influence the bonding within the substance and hence the freezing and melting points. If any intermolecular forces are present more energy must be added to the system to change from a solid to a liquid. This is because the intermolecular bonds have to be overcome to allow the molecules to move more freely. This is less of a change than occurs from the change from liquid to gas, because the molecules are still touching each other in both liquids and solids.

The purity of the compound can influence the temperature at which the solid-liquid change takes place. For example adding sodium chloride (common salt) or another salt to **water** depresses the freezing point, which is why salt is put on roads to stop their icing over. A pure substance has a definite melting or freezing point, the addition of an impurity lowers this temperature as well as spreads it so that there is a less definite, more diffuse melting or freezing point. This means that we can use the freezing or melting point as an indicator of the purity of a substance. When a solid is melted by heating or a liquid frozen while cooled, the temperature remains constant. Thus, if a graph of temperature is plotted against heat added a shoulder or plateau will be seen which represents the freezing or melting point. With an impure substance, this shoulder will not be so precise. A graph of this nature is known as a heating curve. The conversion between solid and liquid occurs at a constant temperature.

With most substances the solid is denser than the liquid phase. As a result of this when freezing the solid will sink to the bottom of the liquid. Water does not behave in this manner. **Ice** is less dense than water and consequently ice will float on water. Water has its maximum density at 39°F (4°C). This is caused by hydrogen bonding, which in the liquid phase is unordered. When the water freezes to form ice, the molecules assume an open ordered pattern that allows the maximum amount of hydrogen bonding. This characteristic has had a profound effect on life on Earth (e.g., it allows **lakes** and streams to freeze at the surface and provide insulation to life underneath the ice during frigid winter months) and results in an active agent of geological change. Because water expands when freezing it is able to crack **rock**; the cyclic freezing and refreezing of water is an important **weathering** agent.

Normally, when we talk about a substance being a solid or a liquid we are referring to its appearance at standard temperature and pressure, this is a pressure of one atmosphere and a temperature of 68°F (20°C). If the melting point is below this temperature and the boiling point is above it then the chemical is a liquid at standard temperature and pressure.

It is possible to cool a liquid below its freezing point and still have it remain as a liquid. This is known as a supercooled liquid. This represents an unstable equilibrium and in time the liquid freezes. It is very easy to supercool water down to 12°F (–11.1°C) and still have it remain a liquid. The supercooled liquid will not start to freeze until there is a point for the ice to start to form. This may be a single piece of dust, which acts as a nucleation point for the ice to start forming. Supercooled water is not encountered in nature because there is too much particulate material in the atmosphere. If any of these particles lands in a supercooled liquid it will instantly turn into the solid form.

Some chemicals do not have a point at which they turn from solid to liquid—they can change directly from solid to gas, a property called sublimation. Dry ice, solid **carbon dioxide**, exhibits this. Like melting and freezing this also happens at one specific temperature.

Solids and liquids are both densely packed at a molecular level. One difference in terms of the molecules is that with a liquid the molecules are more readily capable of slipping over each other. It is this property that makes it easier to pour a liquid. The molecules in a liquid are still touching each adjacent molecule (as they do in a solid), although they are less freely held.

Ionic compounds generally have a higher melting point than covalent compounds. This is because the intermolecular forces in an ionic compound are much stronger. If the pressure is increased the molecules are forced closer together and this means that the intermolecular forces are holding the particles closer together and more tightly, so a higher temperature is required to make the material melt.

Melting is also called fusion, and the energy required to bring about this change of state is called the heat of fusion or the enthalpy of fusion. For ice to turn into liquid water the heat of fusion is 6.01 kJ/mol. Melting and sublimation are both endothermic processes and freezing is an exothermic process. Whenever a material changes from one state to another there is an energy change within the system. For melting the order of the system is decreasing, so energy must be supplied to increase the randomness of the molecules. For freezing the molecules are becoming more ordered, so energy is lost from the system.

Freezing and melting are the change of state from liquid to solid and from solid to liquid. For any given pure chemical they happen at a specific temperature, which is the same for freezing and melting.

See also Chemical bonds and physical properties; Chemical elements; Evaporation; Faults and fractures; Glacial landforms; Glaciation; Glaciers; Glass; Ice heaving and ice wedging; Ice

FRESHWATER

Freshwater is chemically defined as containing a concentration of less than two parts per thousand (<0.2%) of dissolved salts.

Freshwater can occur in many parts of the environment. Surface freshwaters occur in **lakes**, ponds, **rivers**, and streams. Subsurface freshwater occurs in pores in **soil** and in subterranean aquifers in deep geological formations. Freshwater also occurs in snow and glacial **ice**, and in atmospheric vapors, **clouds**, and **precipitation**.

Most of the dissolved, inorganic chemicals in freshwater occur as ions. The most important of the positively charged ions (or cations) in typical freshwaters are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), ammonium (NH_4^{+}), and hydrogen ion (H^{+}). This hydrogen ion is only present if the solution is acidic; otherwise a hydroxy ion (OH^{-}) occurs. The most important of the negatively charged ions (or anions) are sulfate (SO_4^{2-}), chloride (Cl^{-}), and nitrate (NO_3^{-}). Other ions are also present, but in relatively small concentrations. Some freshwaters can have large concentrations of dissolved organic compounds, known as humic substances. These can stain the **water** a deep-brown, in contrast to the transparent color of most freshwaters.

At the dilute end of the chemical spectrum of surface waters are lakes in watersheds with hard, slowly **weathering bedrock** and soils. Such lakes can have a total concentration of salts of less than 0.002% (equivalent to 20 mg/L, or parts per million, ppm). For example, Beaverskin Lake in Nova Scotia has very clear, dilute water, with the most important dissolved chemicals being: chloride (4.4 mg/L), sodium (2.9 mg/L), sulfate (2.8 mg/L), calcium (0.41 mg/L), magnesium (0.39 mg/L), and potassium (0.30 mg/L). A nearby body of water, Big Red Lake, has similar concentrations of these inorganic ions. However, this lake also receives drainage from a nearby bog, and its **chemistry** includes a large concentration of dissolved organic compounds (23 mg/L), which stain the water the color of dark tea.

More typical concentrations of major inorganic ions in freshwater are somewhat larger: calcium 15 mg/L; sulfate 11 mg/L; chloride 7 mg/L; silica 7 mg/L; sodium 6 mg/L; magnesium 4 mg/L; and potassium 3 mg/L.

The freshwater of precipitation is considerably more dilute than that of surface waters. For example, precipitation falling on the Nova Scotia lakes is dominated by sulfate (1.6 mg/L), chloride (1.3 mg/L), sodium (0.8 mg/L), nitrate (0.7 mg/L), calcium (0.13 mg/L), ammonium (0.08 mg/L), magnesium (0.08 mg/L), and potassium (0.08 mg/L). Because the sampling site is within 31 mi (50 km) of the Atlantic Ocean, its precipitation is significantly influenced by sodium and chloride originating with sea sprays. More continental locations have much smaller concentrations of these ions in their precipitation water. For example, precipitation at a remote place in northern Ontario has a sodium concentration of 0.09 mg/L and chloride 0.15 mg/L, compared with 0.75 mg/L and 1.3 mg/L, respectively, at the maritime Nova Scotia site.

See also Clouds and cloud types; Drought; Estuary; Floods; Glaciers; Groundwater; Humidity; Hydrologic cycle; Rapids and waterfalls; Stream capacity and competence; Stream valleys, channels, and floodplains

FUELS AND FUEL CHEMISTRY

A fuel is any compound that has stored energy. This energy is captured in **chemical bonds** through processes such as photosynthesis and respiration. Energy is released during oxidation. The most common form of oxidation is the direct reaction of a fuel with **oxygen** through combustion. Wood, gasoline, **coal**, and any number of other fuels have energy-rich chemical bonds created using the energy from the **Sun**, which is released when the fuel is burned (i.e., the release of chemical energy). Chemical fuels or the fossil fuels are useful reserve of fuels and are therefore used extensively to satisfy the demands of an energy-dependent civilization.

Fossil fuels are principally **hydrocarbons** with minor impurities. They are so named because they originate from the decayed and fossilized remains of plants and animals that lived millions of years ago.

Fossil fuels can be separated into three categories. The first is **petroleum** or oil. This is a mixture of light, simple hydrocarbons dominated by the fractions with 6 to 12 carbons but also containing some light hydrocarbons (e.g., methane and ethane). Fully half of the energy consumed in the United States is from petroleum used to produce fuels for automobiles, recreational vehicles, home heating, or industrial production.

The principal use of petroleum is the production of gasoline. Over 40% all of all production ends up consumed in automobiles and such. Smaller fractions are turned into fuel oil (27%), jet fuel (7.4%), and other miscellaneous fuels, while the small fraction (about 10%) is used for the synthesis of the thousands of petrochemicals used in our daily lives. Indeed, many food compounds and pharmaceuticals owe their synthesis to a petrochemical precursor.

The second most prominent and naturally most abundant fossil fuel is coal. Coal also originates from decayed vegetative material buried eons ago, but the process is slightly different, being less oxidizing. The resulting material still has some of the original lignin-like structure exhibiting many fused rings and a large fraction of aromatic compounds. Consequently, coal is more of a polymeric substance than petroleum and is found as a solid not a liquid. The **carbon** to hydrogen ratio in coal is close to 1:1 (depending upon the type of coal), whereas the carbon to hydrogen ration in petroleum is closer to the 1:2 value expected for a hydrocarbon chain.

Minable coal is defined as 50% of the coal in a seam of at least 12 in thickness. The proven reserves of minable coal are sufficient to supply the industrial needs of modern society for the next four to five hundred years. Unfortunately, as a fuel source, coal has many disadvantages. It is a very dirty fuel that produces a large amount of unburned hydrocarbon, particulate, and—most damaging of all—significant quantities of sulfur dioxide byproducts. Indeed, it is the coal burning power plants of the eastern United States that are responsible for much of the **acid rain** and environmental damage observed in upstate New York and eastern Canada. The other significant disadvantage of coal is that it is not liquid, making it awkward to transport and store and limiting its use in applications like automobiles. A great deal of research has been done on the liquefaction of coal but with little economically viable success.

The third major fossil fuel is **natural gas**. This is a generic term for the light hydrocarbon fractions found associated with most oil deposits. Natural gas is mostly methane with small quantities of ethane and other gases mixed in. It is hydrogen- rich, since methane has a carbon to hydrogen ratio of 1:4. It is also an excellent fuel, burning with a high heat output and little in the way of unwanted pollution. It does produce **carbon dioxide**, which is a greenhouse gas, but all organic compounds also generate carbon dioxide on combustion. Natural gas is also easy to transport through pressurized pipelines.

All of this would appear to make natural gas the perfect fuel. However, it is not without its drawbacks. This includes the presence of hydrogen sulfide in some gas fields, leading to the term "sour gas." Hydrogen sulfide is the smell of rotten eggs, but if smell were the only problem, this would be of little concern. However, hydrogen sulfide is extremely corrosive to the pipes used to transport natural gas and is a very toxic compound being lethal at levels around 1,500 ppm.

In addition, natural gas is potentially explosive as the gas must be maintained under pressure, and any hydrocarbon, in a gaseous state, can explode. This is in contrast to the use of gasoline, which is a much safer fuel. Nevertheless, both the gaseous and liquid forms of hydrocarbons are much more volatile and represent a hazard compared to coal.

It has been suggested that because all of the oxygen in the atmosphere came from the splitting of carbon dioxide via photosynthesis, the total oxygen content may lead to an estimate of the total carbon reserves. However, it is not the total abundance of fuels that is critical—it is the accessibility from both an engineering and economics standpoint that makes near-term global fuel shortages appear probable.

In addition there are serious flaws in the gross estimate of fuels as a significant amount of the world's carbon reserves are tied up in calcium carbonate **rock** formations. Loosely speaking, calcium carbonate is **limestone** and there is abundance of limestone present throughout the world. Accordingly, most industry analysts place available fossil fuel reserves at much lower levels. It is estimated by a wide variety of sources that we will reach maximum oil production in the next twenty years. After that, production will decline worldwide and we will be forced to wean ourselves from an oil-based society. The estimates for coal provide a slightly better prognosis giving a window of about 500 years for consumption of all known reserves.

Natural gas also has one significant advantage over the other fossil fuels: it is "renewable." Natural gas is found as a side product of any decaying material. Methanogenic bacteria—literally, methane-making bacteria—exist in the garbage dumps and **waste disposal** sites of the industrial world, busily producing methane from garbage. Enough that the Fresh Kills garbage dump on Staten Island, New York is capable of heating 16,000 homes.

Various companies have been exploring the use of hydrogen as a fuel. When used in simple combustion, hydrogen has some of the problems associated with natural gas. It must be stored under pressure and is extremely explosive upon ignition in air (e.g. the Hindenburg disaster, in which a hydrogen-filled airship explosively burned). The type of explosion—the shape of the detonation—also makes hydrogen unsuitable as an alternative fuel for the conventional automobile. The sharpness of the explosion would quickly rattle pistons to pieces.

However, hydrogen does not need to be burned directly with oxygen to provide energy. Fuel cells combine hydrogen and oxygen at electrodes to produce **electricity**, which can then be used to run an electric motor or a spacecraft. NASA has been employing hydrogen/oxygen fuel cells for years to provide the electricity for both manned and unmanned spacecraft. In addition, fuel cells have the added bonus of providing crew members with fresh drinking **water**, as the only product of the reaction is pure water. Using fuel cells, hydrogen could potentially be used for conventional automobiles. Questions about storing hydrogen and long-term viability of the fuel cells need to be addressed, but the future of this technology looks promising. At present, however, our economically viable supply of hydrogen is obtained from fossil fuels because hydrogen is released from hydrocarbons during the refining process.

Both the use of sunlight and solar panels to create sufficient electricity to electrolyze water and bacteria capable of splitting water to generate hydrogen and oxygen may make hydrogen the chemical fuel of the future. In addition, research is underway into the use of methanol as a potential partner for a fuel cell, eliminating the need for hydrogen and greatly reducing the difficulties with storage and filling the tank.

The United States leads the world in energy consumption—over 90 quadrillion Btu are used annually in the United States alone (year 2001 estimates).

See also Chemical bonds and physical properties; Energy transformations; Environmental pollution; Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration

FUJITA SCALE • *see* TORNADO

FUJITA, TETSUYA THEODORE

(1920-1998)

Japanese-born American meteorologist

In 1974, Theodore Fujita became the first scientist to identify microburst **wind shear**, a particularly intense and isolated form of **wind** shear later blamed for several devastating airline accidents in the 1980s. The development of Doppler radar allowed Fujita to track and explain the microburst phenomenon, which is now far better understood and avoided by aviators. Fujita also lent his name to the “F Scale” he developed to measure the strength of tornadoes by analyzing the damage they cause on the ground.

Fujita was born in Kitakyushu City, Japan, to Tomojiro, a schoolteacher, and Yoshie (Kanesue) Fujita. Fujita showed an early aptitude for science and obtained the equivalent of a bachelor’s degree in mechanical engineering from the Meji College of Technology in 1943. It was while he was working as an assistant professor of **physics** at Meji that U.S. forces dropped the **atom** bomb on the Japanese cities of Hiroshima and Nagasaki. Fujita visited the ruins three weeks after the bombings. By measuring the scorch marks on bamboo vases in a cemetery in Nagasaki, Fujita was able to show that only one bomb had been dropped. Surveying the damage in Hiroshima, Fujita calculated how high above the ground the bombs had exploded in order to create their unique starburst patterns, which would become important to his later work.

Leaving Meji College in 1949, Fujita became an assistant professor at Kyushu Institute of Technology while pursuing his Ph.D. in atmospheric science at Tokyo University. Like others involved in atmospheric science, he had read the published articles of Horace R. Byers of the University of Chicago, who had conducted groundbreaking research on thunderstorms in 1946 and 1947. Fujita translated two of his own articles on the same subject into English and sent them to Byers. Byers was impressed with Fujita’s work and the two men began a correspondence. In 1953, the year Fujita received his doctorate, Byers extended an invitation to the Japanese scientist to work at the University of Chicago as a visiting research associate.

Fujita worked at the University as a senior meteorologist until 1962, when he became an associate professor. For two years beginning in 1961, he was the director of the Mesometeorological Research Project, and in 1964, Fujita became the director of the **Satellite** and Mesometeorology Research Project. Fujita was made a full professor in 1965, and held the Charles E. Merriam Distinguished Service Professorship on an active basis and on an emeritus basis. He became a naturalized U.S. citizen in 1968, and adopted the first name Theodore for use in the United States. He married Sumiko Yamamo in June, 1969, and has a son from his first marriage.

From the mid–1960s, Fujita and his graduate students did extensive aerial surveys of tornadoes. Fujita claims to have logged over 40,000 miles flying in small planes under the worst of **weather** conditions. In the late 1960s, Fujita developed his **tornado** “F Scale.” Traditionally, meteorologists listed only the total number of tornadoes that occurred, having no objective way to measure storm strength. Fujita constructed a system of measurement that correlates ground damage to windspeed. His six point system operates on an F–0 to F–5 scale and is similar to the **Richter scale** used to measure the strength of earthquakes.

Fujita did not actually witness a tornado until June 12, 1982, so the mainstay of his work was research on the aftermath of tornadoes. While at the National Center for Atmospheric Research in Denver, Colorado, Fujita spotted a tornado in the region early and collected some of the best data on the phenomenon ever.

In 1974, Fujita began analyzing the phenomenon of microbursts. Flying over the devastation wrought by a tornado, he noticed patterns of damage similar to those he had witnessed in Hiroshima and Nagasaki. “If something comes down from the sky and hits the ground it will spread out; it will produce the same kind of outburst effect that was in the back of my mind, from 1945 to 1974," Fujita explained in *The Weather Book: An Easy to Understand Guide to the U.S.A.'s Weather.* Meteorologists knew by the mid–1970s that severe storms produce **downdrafts**, but they assumed those downdrafts lost most of their force before they hit the ground and, therefore, did not cause much damage, so the phenomenon was largely ignored. Encouraged by Byers, Fujita coined the term "downburst" and began research to prove his thesis that downdraft is a significant weather phenomenon. Aided by the National Center for Atmospheric Research, he set up a project near Chicago that detected 52 downbursts in 42 days.

Fujita was eventually able to show that downdrafts cause so-called wind shear, a sudden and dramatic change in wind velocity, which causes damage on the ground and is a particular hazard in aviation, especially to planes taking off, landing, or flying low. Windspeeds up to F–3 are common for downbursts (higher F Scale readings usually indicate tornadoes). Fujita has commented that a lot of damage attributed to tornadoes in the past has really been the work of downbursts. "After I pointed out the existence of downbursts, the number of tornadoes listed in the United States decreased for a number of years," Fujita noted in *The Weather Book*.

Fujita's research finally gained national attention in the 1980s. Wind shear caused by downdraft was cited as a contributing factor in the July 1982, crash of a Pan American 727 in New Orleans, Louisiana, which killed 154 people. During that event, the airliner was observed sinking back to the ground shortly after takeoff—the apparent result of wind shear. Another accident occurred in August 1985, when Delta Flight 191 crashed at Dallas-Ft. Worth Airport, killing 133 people. Again, wind shear was suspected to be the immediate cause of the catastrophe.

Air safety has improved dramatically because of Fujita's work, which led to the development of Doppler radar. Doppler radar is so sensitive it actually picks up particles of debris in the air that are as fine as dust. Movements of these particles are tracked to measure shifts in wind velocity. "This is particularly important in being able to detect the precursor events for severe weather," Frank Lepore, public affairs officer for the National Weather Service, told Joan Oleck in an interview. By 1996, the Weather Service and U.S. Air Force together installed 137 Doppler systems, essentially blanketing the continental United States. Harking back to the airline accidents of the 1980s, Lepore noted "a reduction in those incidents today because there is Doppler radar available. By being able to measure the internal velocity of air moving inside a storm system, [aviators] can see rising and falling volumes of air.... They're now getting 20- and 25-minute warning on the systems that cause tornadoes."

In 1988, Fujita assumed directorship of the Wind Research Lab at the University of Chicago. Among his many awards were the 1989 Medaille de Vermeil from the French National Academy of Air and Science for identifying microbursts; the 1990 Fujiwara Award Medal from the Meteorological Society of Japan for his research on mesometeorology; the 1991 Order of the Sacred Treasure, Gold and Silver Star from the Government of Japan for his tornado and microburst work; and the 1992 Transportation Cultural Award from the Japanese Government for his contributions to air safety. Fujita died in Chicago at the age of 78.

FUMAROLE

Any opening in the ground that emits hot steam or gas is a fumarole. Fumaroles are common on the flanks of volcanoes as well as in their craters and calderas. Extensive fumarole fields occur in areas where a shallow volcanic heat source is overlaid by water-permeable **rock**, as at Yellowstone National Park in the United States and Rotorua in New Zealand.

All fumaroles require both heat and a source of gas or **water**. They are most often supplied with heat and gas by **magma** or masses of freshly ejected volcanic rock and with water by **precipitation** that seeps into the ground. Subterranean heated water also produces hot **springs** and geysers; hot springs are more common than fumaroles, geysers less common. Geysers are distinguished from both hot springs and fumaroles by their specialized plumbing systems, while the difference between a hot spring and a fumarole is simply the degree of heating. If the heat source is not strong enough to boil water, the result is a hot spring. Even if water is boiled, the resulting steam may be condensed by passing through liquid **groundwater** before reaching the surface, in which case the result is still a hot spring. Only if steam reaches the surface is a fumarole produced. Some vents are hot springs in the wet season and fumaroles in the dry, when there is less groundwater to condense steam rising from below.

A deposit of hot ash and shattered rock laid down by an explosive volcanic eruption may cover many square miles of ground and be hundreds of feet deep. During the years it takes to cool, such a deposit may produce a vast field of fumaroles. This occurred in the Valley of Ten Thousand Smokes in Alaska, where a thick ash-and-rock layer was laid down by a large eruption in 1912. Immediately after deposition, this layer was dotted by tens of thousands of fumaroles, some venting from openings many feet across. Over the next half-century, as the underlying mass cooled, most of these fumaroles became extinct.

Fumaroles whose gases are particularly sulfurous are termed solfataras. (Some geologists use the terms fumarole and solfatara synonymously regardless of sulfur content.) Furthermore, some gas-emitting vents have temperatures below the boiling point of water and emit mostly **carbon dioxide** (CO_2) and other gases with little water vapor; geologists term such dry, cool vents mofettes to distinguish them from fumaroles.

See also Crater, volcanic; Hydrothermal processes; Volcanic vent

FUSION • *see* NUCLEAR FUSION

G

GAGARIN, YURI A. (1934-1968)

Russian cosmonaut

Yuri A. Gagarin was the first human in **space**. In 1961, the boyish-looking Soviet cosmonaut captured the attention of the world with his short flight around the earth. "He invited us all into space," American astronaut **Neil Armstrong** said of him, as quoted in *Aviation Week and Space Technology*.

The third of four children, Yuri Alekseevich Gagarin was born on a collective farm in Klushino, in the Smolensk region of the Russian Federation. His father, Aleksey Ivanovich Gagarin, was a carpenter on the farm and his mother, Anna, a dairymaid. Gagarin grew up helping them with their work. Neither of his parents had much formal education, but they encouraged him in his schooling. During World War II, the family was evicted from their home by invading German troops, and Gagarin's older brother and sister were taken prisoner for slave labor, though they later escaped.

After the war, Gagarin went to vocational school in Moscow, originally intending to become a foundry worker, and then he moved on to the Saratov Industrial Technical School. He was still learning to be a foundryperson, although his favorite subjects were **physics** and mathematics. In 1955, during his fourth and final year of school, he joined a local flying club. His first flight as a passenger, he later wrote in *Road to the Stars*, "gave meaning to my whole life." He quickly mastered flying, consumed by a new determination to become a fighter pilot. He joined the Soviet Air Force after graduation. The launch of Sputnik—the first artificial **satellite** sent into space—occurred on October 4, 1957, while he pursued his military and flight training. He graduated with honors that same year and married medical student Valentina Ivanova Goryacheva. They would have two children, a daughter and a son.

Gagarin volunteered for service in the Northern Air Fleet and joined the Communist Party. He followed closely news of other Sputnik launches; although there had been no official announcement, Gagarin guessed that preparations for manned flights would soon begin and he volunteered for cosmonaut duty. Gagarin completed the required weeks of physical examinations and testing in 1960, just before his twenty-sixth birthday. He was then told that he had been made a member of the first group of twelve cosmonauts. The assignment was a secret, and he was forbidden to tell even his wife until his family had settled into the new space-program complex called Zvezdniy Gorodok (Star Town), forty miles from Moscow. An outgoing, natural leader, the stocky, smiling Gagarin stood out even among his well-qualified peers. Sergei Korolyov, the head of the Soviet space program and chief designer of its vehicles, thought Gagarin had the makings of a first-rate scientist and engineer, as well as being an excellent pilot. In March of 1961, Korolyov approved the selection of Gagarin to ride Vostok I into orbit.

Senior Lieutenant Gagarin made history on April 12, 1961, when a converted ballistic missile propelled his Vostok capsule into Earth orbit from the remote Baikonur Cosmodrome. The Vostok was controlled automatically, and Gagarin spent his time reporting observations of the Earth and his own condition. He performed such tasks as writing and tapping out a message on a telegraph key, thus establishing that a human being's coordination remained intact even while weightless in space. Proving that people could work in space, he also ate and drank to verify that the body would take nourishment in weightlessness. He commented repeatedly on the beauty of the earth from space and on how pleasant weightlessness felt.

Gagarin rode his spacecraft for 108 minutes, ejecting from the spherical reentry module after the craft reentered the atmosphere just short of one complete orbit. Ejection was standard procedure for all Vostok pilots, although Gagarin dutifully supported the official fiction that he had remained in his craft all the way to the ground—a requirement for international certification of the flight as a record. Cosmonaut and capsule landed safely near the banks of the Volga River.

After doctors proclaimed him unaffected by his flight, Gagarin was presented to the public as an international hero. He received an instant promotion to the rank of major and made appearances around the world. He was named a Hero of the Soviet Union and a Hero of Socialist Labor, and he became an honorary citizen of fourteen cities in six countries. He received the Tsiolkovsky Gold Medal of the Soviet Academy of Sciences, the Gold Medal of the British Interplanetary Society, and two awards from the International Aeronautical Federation. The flight had many implications for international affairs: American leaders extended cautious congratulations and redoubled their own efforts in the space race, while the Soviet media proclaimed that Gagarin's success showed the strength of socialism.

Gagarin became commander of the cosmonaut team. In 1964, he was made deputy director of the cosmonaut training center at the space program headquarters complex—where he oversaw the selection and training of the first women cosmonauts. He served as capsule communicator—the link between cosmonauts and ground controllers—for four later space flights in the Vostok and Voskhod programs. At various times during this period, he also held political duties; he chaired the Soviet-Cuban Friendship Society and served on the Council of the Union and the Supreme Soviet Council of Nationalities.

Gagarin always wanted to venture back to space, and in 1966, he was returned to active status to serve as the backup cosmonaut to Vladimir Komarov for the first flight of the new Soyuz spacecraft. When the Soyuz 1 mission ended and Komarov died due to a parachute malfunction, Gagarin was assigned to command the upcoming Soyuz 3. But Gagarin himself did not live to fly the Soyuz 3 mission. On March 27, 1968, he took off for a routine proficiency flight in a two-seat MiG–15 trainer. He and his flight instructor became engaged in low-level maneuvers with two other jets. Gagarin's plane crossed close behind another jet and was caught in its vortex; he lost control and the jet crashed into the tundra at high speed, killing both occupants instantly.

Gagarin was given a hero's funeral. The Cosmonaut Training Center was renamed in his honor, as were his former hometown, a space tracking ship, and a lunar crater. His wife continued to work as a biomedical laboratory assistant at Zvezdniy Gorodok, and Gagarin's office there was preserved as a museum; a huge statue of him was erected in Moscow. His book *Survival in Space* was published posthumously. Written with space-program physician Vladimir Lebedev, the work outlines Gagarin's views on the problems and requirements for successful long-term space flights. On April 12, 1991, thirty years after Gagarin's flight, his cosmonaut successors, along with eighteen American astronauts, gathered at Baikonur to salute his achievements.

See also History of manned space exploration

GAIA HYPOTHESIS

The Gaia hypothesis is a recent and controversial theory that views Earth as an integrated, pseudo-organismic entity, and not as a mere physical object in **space**. Gaia, Earth, was believed by the ancient Greeks to be a living, fertile ancestor of many of their important gods. The Gaia hypothesis suggests that organisms and ecosystems on Earth cause substantial changes to occur in the physical and chemical nature of the environment, in a manner that improves the living conditions on the planet. In other words, it is suggested that Earth is an organismic planet, with homeostatic mechanisms that help to maintain its own environments within the ranges of extremes that can be tolerated by life. According to the Gaian hypothesis, **evolution** is the result of cooperative, not competitive processes. The Gaian hypothesis holds that evolution of life on Earth was enhanced by two processes: sexual reproduction, which introduced enormous variety in the gene pool, and the development of consciousness, which enabled genetic methods of evolution to be replaced with more efficient social mechanisms.

Earth is the only planet in the universe that is known to support life. This is one of the reasons why the Gaia hypothesis cannot be tested by rigorous, scientific experimentation—there is only one known replicate in the great, universal experiment. However, some supporting evidence for the Gaia hypothesis can be marshaled from certain observations of the structure and functioning of the planetary ecosystem.

One supporting line of reasoning for the Gaia hypothesis concerns the presence of **oxygen** in Earth's atmosphere. Scientists believe that the primordial atmosphere of Earth did not contain oxygen. The appearance of this gas required the evolution of photosynthetic life forms, which were initially blue-green bacteria and, somewhat later, single-celled algae. Molecular oxygen is a waste product of photosynthesis, and its present atmospheric concentration of about 21% has entirely originated with this biochemical process (which is also the basis of all biologically fixed energy in ecosystems). Of course, the availability of atmospheric oxygen is a critically important environmental factor for most of Earth's species and for many ecological processes. In addition, it appears that the concentration of oxygen in the atmosphere has been relatively stable for an extremely long period of time, perhaps several billions of years. This suggests the existence of a long-term equilibrium between the production of this gas by green plants, and its consumption by biological and non-living processes. If the atmospheric concentration of oxygen were much larger than it actually is, say about 25% instead of the actual 21%, then biomass would be much more readily combustible. These conditions could lead to much more frequent and more extensive forest fires. Such conflagrations would be severely damaging to Earth's ecosystems and species.

Some proponents of the Gaia hypothesis interpret the above information to suggest that there is a planetary, homeostatic control of the concentration of molecular oxygen in the atmosphere. This control is intended to strike a balance between the concentrations of oxygen required to sustain the metabolism of organisms, and the larger concentrations that could result in extremely destructive, uncontrolled wildfires.

Another line of evidence in support of the Gaian theory concerns **carbon dioxide** in Earth's atmosphere. To a substantial degree, the concentration of this gas is regulated by complex biological and physical processes by which **carbon dioxide** is emitted and absorbed. This gas is well known to be important in the planet's **greenhouse effect**, which is critical to maintaining the average **temperature** of the surface within a range that organisms can tolerate. It has been estimated that in the absence of this greenhouse effect, Earth's average surface temperature would be about –176°F (–116°C), much too cold for organisms and ecosystems to tolerate over the longer term. Instead, the existing greenhouse effect, caused in large part by atmospheric carbon dioxide, helps to maintain an average surface temperature of about 59°F (15°C). This is within the range of temperature that life can tolerate.

Again, advocates of the Gaia hypothesis interpret these observations to suggest that there is a homeostatic system for control of atmospheric carbon dioxide, and of climate. This system helps to maintain conditions within a range that is satisfactory for life.

All scientists agree that there is clear evidence that the non-living environment has an important influence on organisms, and that organisms can cause substantial changes in their environment. However, there appears to be little widespread support within the scientific community for the notion that Earth's organisms and ecosystems have somehow integrated in a mutually benevolent symbiosis (or mutualism), aimed at maintaining environmental conditions within a comfortable range.

Still, the Gaia hypothesis is a useful concept, because it emphasizes the diverse connections of ecosystems, and the consequences of human activities that result in environmental and ecological changes. Today, and into the foreseeable future, humans are rapidly becoming a dominant force that is causing large, often degradative changes to Earth's environments and ecosystems. Hopefully, the changes wrought by humans will not exceed the limits of homeostatic tolerance and repair of the planet and its ecological components. If these possibly Gaian limits of tolerance are exceeded, some scientists assert the consequences could be catastrophic for life on Earth.

See also Earth (planet); Evolutionary mechanisms; Evolution, evidence of

GALILEI, GALILEO (1564-1642)

Italian mathematician and astronomer

Galileo Galilei is credited with establishing the modern experimental method. Before Galileo, knowledge of the physical world that was advanced by scientists and thinkers was for the most part a matter of hypothesis and conjecture. In contrast, Galileo introduced the practice of proving or disproving a scientific theory by conducting tests and observing the results. His desire to increase the precision of his observations led him to develop a number of inventions and discovery, particularly in the fields of **physics** and **astronomy**.

The son of Vincenzo Galilei (c.1520–1591), an eminent composer and music theorist, Galileo was born in Pisa. He received his early education at a monastery near Florence, and in 1581, entered the University of Pisa to study medicine. While a student he observed a hanging lamp that was swinging back and forth, and noted that the amount of time it took the lamp to complete an oscillation remained constant, even as the arc of the swing steadily decreased. He later experimented with other suspended objects and discovered that they behaved in the same way, suggesting to him the principle of the pendulum. From this discovery he was able to invent an instrument that measured time, which doctors found to be useful for measuring a patient's pulse rate, and Christiaan Huygens later adapted the principle of a swinging pendulum to build a pendulum clock.

While at the University of Pisa, Galileo listened in on a geometry lesson and afterward abandoned his medical studies to devote himself to mathematics. However, he was unable to complete a degree at the university due to lack of funds. He returned to Florence in 1585, having studied the works of Euclid and Archimedes. He expanded on Archimedes' work in hydrostatics by creating a hydrostatic balance, a device designed to measure the density of objects. The following year, he published an essay describing his new invention, which determined the specific **gravity** of objects by weighing them in **water**. With the hydrostatic balance, Galileo gained a scientific reputation throughout Italy.

In 1592, Galileo was appointed professor of mathematics at Padua University in Pisa, where he conducted experiments with falling objects. Aristotle had stated that a heavier object should fall faster than a lighter one. It is said that Galileo tested Aristotle's assertion by climbing the leaning tower of Pisa, dropping objects of various weights, and proving conclusively that all objects, regardless of weight, fall at the same rate.

Some of Galileo's experiments did not turn out as expected. He tried to determine the speed of light by stationing an assistant on a hill while he stood on another hill and timed the flash of a lantern between the hills. He failed because the hilltops were much too close together to make a measurement.

In 1593, Galileo invented one of the first measuring devices to be used in science: the thermometer. Galileo's thermometer employed a bulb of air that expanded or contracted as **temperature** changed and in so doing caused the level of a column of water to rise or fall. Though this device was inaccurate because it did not account for changes in air pressure, it was the forerunner of improved instruments.

From 1602 to 1609, Galileo studied the motion of pendulums and other objects along arcs and inclines. Using inclined planes that he built, he concluded that falling objects accelerate at a constant rate. This law of uniform acceleration later helped Isaac Newton derive the law of gravity.

Galileo did not make his first contribution to astronomy until 1604, when a supernova abruptly exploded into view. Galileo postulated that this object was farther away than the planets and pointed out that this meant that Aristotle's "perfect and unchanging heavens" were not unchanging after all. Ironically, Galileo's best-known invention, the **telescope**, was *not* his creation after all. The telescope was actually invented in 1608 by **Hans Lippershey**, a Danish spectacle maker. When Galileo learned of the invention in mid-1609, he quickly built one himself and made several improvements. His altered telescope could magnify objects at nine-power, three times the magnification of Lippershey's model. Galileo's telescope proved to be very valuable for maritime applications, and

Galileo, pleading at his trial before the Inquisition. © *Corbis-Bettmann. Reproduced by permission.*

Galileo was rewarded with a lifetime appointment to the University of Venice.

He continued his work, and by the end of the year he had built a telescope that could magnify at 30-power. The discoveries he made with this instrument revolutionized astronomy. Galileo saw jagged edges on the **Moon**, which he realized were the tops of mountains. He assumed that the Moon's large dark areas were bodies of water, which he called maria ("seas"), though we now know there is no water on the Moon. When he observed the Milky Way, Galileo was amazed to discover Jupiter, which resulted in his discovery of its four moons; he later called them "satellites," a term suggested by the German astronomer **Johannes Kepler**. Galileo named the moons of Jupiter, Sidera Medicea ("Medicean stars") in honor of Cosimo de Medici, the Grand Duke of Tuscany, whom Galileo served as "first philosopher and mathematician" after leaving the University of Pisa in 1610. Also, with repeated observation, he was able to watch the moons as they were being eclipsed by Jupiter and from this he was able to correctly estimate the period of **rotation** of each of the moons.

In 1610, Galileo outlined planetary discoveries in a small book called *Siderus Nuncius* ("The Sidereal Messenger"). Venus, seen through the telescope, exhibited phases like the Moon, and for the same reasons: Venus did not produce its own light but was illuminated by the **Sun**.

Saturn was a mystery: Galileo's 30-power telescope was at the limit of its ability to resolve Saturn, and the planet appeared to have three indistinct parts. When Galileo looked at the Sun, he saw dark spots on its disc. The position of the spots changed from day to day, allowing Galileo to determine the rotational rate of the Sun.

In 1613, Galileo published a book in which for the first time he presented evidence for and openly defended the model of the **solar system** earlier proposed by the Polish astronomer Nicholas Copernicus, who argued that Earth, rather than being positioned at the center of the universe, as in the Ptolemaic design, was only one of several galactic bodies that orbited the Sun. While there was some support even among ecclesiastical authorities for Galileo's proof of the Copernican theory, the Roman Catholic hierarchy ultimately determined that a revision of the long-held astronomical doctrines of the church was unnecessary. Thus, in 1616, a decree was issued by the church declaring the Copernican system "false and erroneous," and Galileo was ordered not to support this system.

Following this run-in with the Catholic Church and the inquisition that forced his adherence to the Copernican theory of the solar system, Galileo focused on the problem of determining **longitude** at sea, which required a reliable clock. Galileo thought it possible to measure time by observing eclipses of Jupiter's moons. Unfortunately, this idea was not practical for eclipses could not be predicted with enough accuracy and observing celestial bodies from a rocking ship was nearly impossible.

Galileo wanted to have the edict against the Copernican theory revoked, and in 1624, traveled to Rome to make his appeal to the newly elected pope, Urban VIII. The pope would not revoke the edict but did give Galileo permission to write about the Copernican system, with the provision that it would not be given preference to the church-sanctioned Ptolemaic model of the universe.

With Urban's imprimatur, Galileo wrote his *Dialogue Concerning the Two Chief World Systems—Ptolemaic and Copernican*, which was published in 1632. Despite his agreement not to favor the Copernican view, the objections to it in the *Dialogue* are made to sound unconvincing and even ridiculous. Summoned to Rome to stand before the Inquisition, Galileo was accused of violating the original proscription of 1616 forbidding him to promote the Copernican theory. Put on trial for heresy, he was found guilty and ordered to recant his errors. At some point during this ordeal Galileo is supposed to have made his famous statement: "And yet it moves," referring to the Copernican doctrine of Earth's rotation on its axis.

While the judgment against Galileo included a term of imprisonment, the pope commuted this sentence to house arrest at Galileo's home near Florence. Although he was forbidden to publish any further works, he devoted himself to his work on motion and parabolic trajectories, arriving at theories that were later refined by others and made an important impact on gunnery. Galileo died blind at the age of 78.

See also Gravity and the gravitational field

GEIGER COUNTER • *see* FISSION

GELL-MANN, MURRAY (1929-)

American physicist

Prior to the 1940s and 1950s, only a handful of fundamental particles—among them the proton, neutron, electron, and positron—had been discovered in particle **physics** research. The study of cosmic rays and particle accelerator reactions revealed that the composition of matter was much more complex than previously thought. Dozens, and then hundreds of new particles were discovered. Most appeared to meet the criterion of being a basic form of matter, but they often had unexpected properties. For example, some had lifetimes much longer (10^{-9} second) than was predicted for them, based on their mass. Because of these properties, they were collectively referred to as "strange" particles. Before long, physicists aggressively began searching for a way to organize and make sense out of the particle zoo they had discovered. A leading figure in this search was Murray Gell-Mann.

Gell-Mann was born in New York City in 1929. He earned his bachelor of science degree at Yale University at the age of nineteen and his Ph.D. from the Massachusetts Institute of Technology three years later. He worked briefly at the Institute for Advanced Studies and then taught at the University of Chicago from 1952 to 1954. Gell-Mann then moved to the California Institute of Technology, where he became R.A. Millikan professor of theoretical physics in 1966.

Gell-Mann has made a number of contributions to the effort to organize the "particle zoo." In 1953, he suggested that basic particles contain an intrinsic property known as "strangeness," not unlike charge or spin. He showed how the conservation of strangeness in a particle reaction could explain a number of observations made of these new particles. A similar concept was developed independently by the Japanese physicist, Kazuhiko Nishijima.

Gell-Mann next applied himself to the development of a system for placing the known elementary particles into a small number of groups. He observed that particles could be classified into a relatively small number of families of multiplets that have similar properties. Gell-Mann referred to his classification system as *the eight-fold way*, after the eight ways of right living taught by the Buddha.

Gell-Mann's scheme accomplished for elementary particles what Dmitri Mendeleev's **periodic table** had achieved for the elements. Furthermore, like the periodic table, the eight-fold way predicted the existence of new elementary particles. The discovery in 1964 of one such particle, the omega minus (Ω–) provided dramatic confirmation of Gell-Mann's ideas. The Israeli physicist, Yuval Ne'emann, independently proposed a similar system of classification at about the same time.

Finally, Gell-Mann suggested that the hundreds of elementary particles might, in fact, be composed of a very small number of even more basic particles. He called these particles quarks, from James Joyce's *Finnegan's Wake*, "Three quarks for Master Mark!" The first three quarks to be discovered were given the somewhat whimsical names of "up," "down," and "strange." Gell-Mann has also made important contributions to the theory of quantum chromodynamics, which attempts to explain interactions among quarks.

See also Atomic structure; Quantum theory and mechanics

GEMSTONES

Gemstones are **minerals** or other materials that, because of certain outstanding physical properties such as color, clarity, and hardness, have aesthetic value for use in jewelry and other adornments. Of the over 3,000 different mineral varieties known, about 50 are commonly used as gemstones. In general, for a mineral to be used as a gemstone it must be beautiful when polished, cut, or faceted, and it must be hard and durable. Rarity is another characteristic that lends value to a gemstone.

Most gemstones are minerals, but gemstones are given a name based on their appearance, as opposed to the more scientifically strict names of minerals. As a result, a mineral may have a different name for its gem version. For example, sapphire and ruby, two well-known gemstones of distinctly different color, are actually the same mineral: corundum. Emerald and aquamarine are gem forms of beryl. **Quartz** is called amethyst if it is purple, citrine if yellow. Other gemstones are known by their mineral name such as **diamond**, garnet, and topaz.

Although a gemstone may have many properties that make it appealing, the beauty of a gemstone is generally a factor of its color, clarity, and luster. The color of a gem is largely due to its chemical composition. If the color is the result of elements that are an essential part of the mineral structure, it is termed idiochromatic. These minerals usually produce gems of a consistent color, such as peridot (mineral name: **olivine**), which is always green. An allochromatic gem derives its color from elemental impurities that are not integral to mineral. In this case, a mineral can vary in color, based on the varying trace impurities. Corundum, for example, is white in the pure mineral state, but slight amounts of chromium and **iron** will produce the red color of rubies while a combination of iron and titanium will result in sapphire blue. The color variation in diamond and quartz are also due to chemical impurities.

The clarity is the degree to which a gemstone is free of visible impurities, or inclusions. Inclusions may be tiny gas bubbles trapped in the crystal, internal fractures, or microscopic specks of a differing mineral. Inclusions are a very common result of the natural formation processes of minerals and it is the exception to find a mineral free of them and is why the most valued gems are free of inclusions. Some minerals have a greater tendency to contain inclusions, such as emerald.

The luster of a gemstone is the overall appearance as light strikes it. Gemstones are valued for a luster that is very shiny and glasslike and for one that yields a high degree of internal reflections. The latter, termed **adamantine**, is enhanced greatly by faceting, or the grinding of regular, angled surfaces. There are numerous patterns of faceting that are designed to maximize the natural luster of a gemstone. Diamond is a prime example of how faceting brings out its natural brilliance. Chatoyancy in gemstones, commonly known as “cat’s eyes” or “stars,” occurs when light reflects perpendicularly from mineral channels or mineral fibers inside the gemstone. Parallel fibers will result in a cat’s eye effect; when the reflecting fibers extend in different directions, a star effect will result.

Not all gemstones are minerals. Some are naturally occurring organic materials. The popular gemstone amber, for example, is fossilized tree resin. Another, pearl, is produced when an oyster attempts to isolate a foreign particle within its shell by coating it with the same material that lines its shell: mother-of-pearl. In addition, many gemstones are now synthesized and produced in large quantities in factories.

See also Industrial minerals; Minerology

GEOCENTRIC MODEL • *see* ASTRONOMY

GEOCHEMISTRY

Geochemistry is the study of the chemical processes that form and shape the earth.

Earth is essentially a large mass of crystalline solids that are constantly subject to physical and chemical interaction with a variety of solutions (e.g., **water**) and substances. These interactions allow a multitude of chemical reactions.

It is through geochemical analysis that estimates of the age of Earth are formed. Because radioactive isotopes decay at measurable and constant rates (e.g., **half-life**) that are proportional to the number of radioactive atoms remaining in the sample, analysis of rocks and **minerals** can also provide reasonably accurate determinations of the age of the formations in which they are found. The best measurements obtained via radiometric dating (based on the principles of nuclear reactions) estimate the age of Earth to be four and one half billion years old.

Dating techniques combined with spectroscopic analysis provide clues to unravel Earth’s history. Using neutron activation analysis, Nobel Laureate Luis Alvarez discovered the presence of the element iridium when studying samples from the K-T boundary layer (i.e., the layer of sediment laid down at the end of the Cretaceous and beginning of the Tertiary Periods). Fossil evidence shows a mass extinction at the end of the **Cretaceous Period**, including the extinction of the dinosaurs. The uniform iridium layer—and presence of **quartz crystals** with shock damage usually associated only with large asteroid impacts or nuclear explosions—advanced the hypothesis that a large asteroid impact caused catastrophic climatic damage that spelled doom for the dinosaurs.

Although hydrogen and helium comprise 99.9% of the atoms in the universe, Earth’s **gravity** is such that these elements readily escape Earth’s atmosphere. As a result, the hydrogen found on Earth is found bound to other atoms in molecules.

Geochemistry generally concerns the study of the distribution and cycling of elements in the **crust** of the earth. Just as the biochemistry of life is centered on the properties and reaction of **carbon**, the geochemistry of Earth’s crust is centered upon **silicon**. Also important to geochemistry is **oxygen**. Oxygen is the most abundant element on Earth. Together, oxygen and silicon account for 74% of Earth’s crust.

The type of **magma** (Basaltic, Andesitic or Ryolytic) extruded by volcanoes and fissures (magma is termed **lava** when at Earth’s surface) depends on the percentage of silicon and oxygen present. As the percentage increases, the magma becomes thicker, traps more gas, and is associated with more explosive eruptions.

The eight most common elements found on Earth, by weight, are oxygen (O), silicon (Si), **aluminum** (Al), **iron** (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg).

Unlike carbon and biochemical processes where the covalent bond is most common, however, the ionic bond is the most common bond in **geology**. Accordingly, silicon generally becomes a cation and will donate four electrons to achieve a noble gas configuration. In quartz, each silicon **atom** is coordinated to four oxygen atoms. Quartz crystals are silicon atoms surrounded by a tetrahedron of oxygen atoms linked at shared corners.

Rocks are aggregates of minerals and minerals are composed of elements. A mineral has a definite (not unique) formula or composition. Diamonds and **graphite** are minerals that are polymorphs (many forms) of carbon. Although they are both composed only of carbon, diamonds and graphite have very different structures and properties. The types of bonds in minerals can affect the properties and characteristics of minerals.

Pressure and **temperature** affect the structure of minerals. Temperature can determine which ions can form or remain stable enough to enter into chemical reactions. **Olivine**, ($(Fe, Mg)_2 SiO_4$), for example is the only solid that will form at

1,800°C. According to olivine's formula, it must be composed of two atoms of either Fe or Mg. Olivine is built by the ionic substitution of Fe and Mg—the atoms are interchangeable because they the same electrical charge and are of similar size—and thus, olivine exists as a range of elemental compositions termed a **solid solution series**. Olivine can thus be said to be "rich" in iron or rich in magnesium. As magma cools larger atoms such as potassium ions enter into reactions and additional minerals form.

The determination of the chemical composition of rocks involves the crushing and breakdown of rocks until they are in small enough pieces that decomposition by hot acids (hydrofluoric, nitric, hydrochloric, and perchloric acids) allows the elements present to enter into solution for analysis. Other techniques involve the high temperature fusion of powdered inorganic reagent (flux) and the **rock**. After **melting** the sample, techniques such as x-ray fluorescence spectrometry may be used to determine which elements are present.

Chemical and mechanical **weathering** break down rock through natural processes. Chemical weathering of rock requires water and air. The basic chemical reactions in the weathering process include solution (disrupted ionic bonds), hydration, hydrolysis, and oxidation.

The geochemistry involved in many environmental issues has become an increasing important aspect of scientific and political debate. The effects of **acid rain** are of great concern to geologists not only for the potential damage to the **biosphere**, but also because acid rain accelerates the weathering process. Rainwater is made acidic as it passes through the atmosphere. Although rain becomes naturally acidic as it contacts nitrogen, oxygen, and **carbon dioxide** in the atmosphere, many industrial pollutants bring about reactions that bring the acidity of rainwater to dangerous levels. Increased levels of carbon dioxide from industrial pollution can increase the formation of carbonic acid. The rain also becomes more acidic. **Precipitation** of this "acid rain" adversely affects both geological and biological systems.

According to plate tectonic theory, the crust (**lithosphere**) of Earth is divided into shifting plates. Geochemical analysis of Earth's tectonic plates reveals a continental crust that is older, thicker and more granite-like than the younger, thinner oceanic crusts made of basaltic (iron, magnesium) materials.

See also Atomic mass and weight; Atomic number; Atomic structure; Big Bang theory; Chemical bonds and physical properties; Chemical elements; Geologic time

GEOGRAPHIC AND MAGNETIC POLES

Earth's geographic poles are fixed by the axis of Earth's **rotation**. On maps, the north and south geographic poles are located at the congruence of lines of **longitude**. Earth's geographic poles and magnetic poles are not located in the same place—in fact they are hundreds of miles apart. As are all points on Earth, the northern magnetic pole is south of the northern geographic pole (located on the **polar ice** cap) and is presently located near Bathurst Island in northern Canada, approximately 1,000 mi (1,600 km) from the geographic North Pole. The southern magnetic pole is displaced hundreds of miles away from the southern geographic pole on the Antarctic continent.

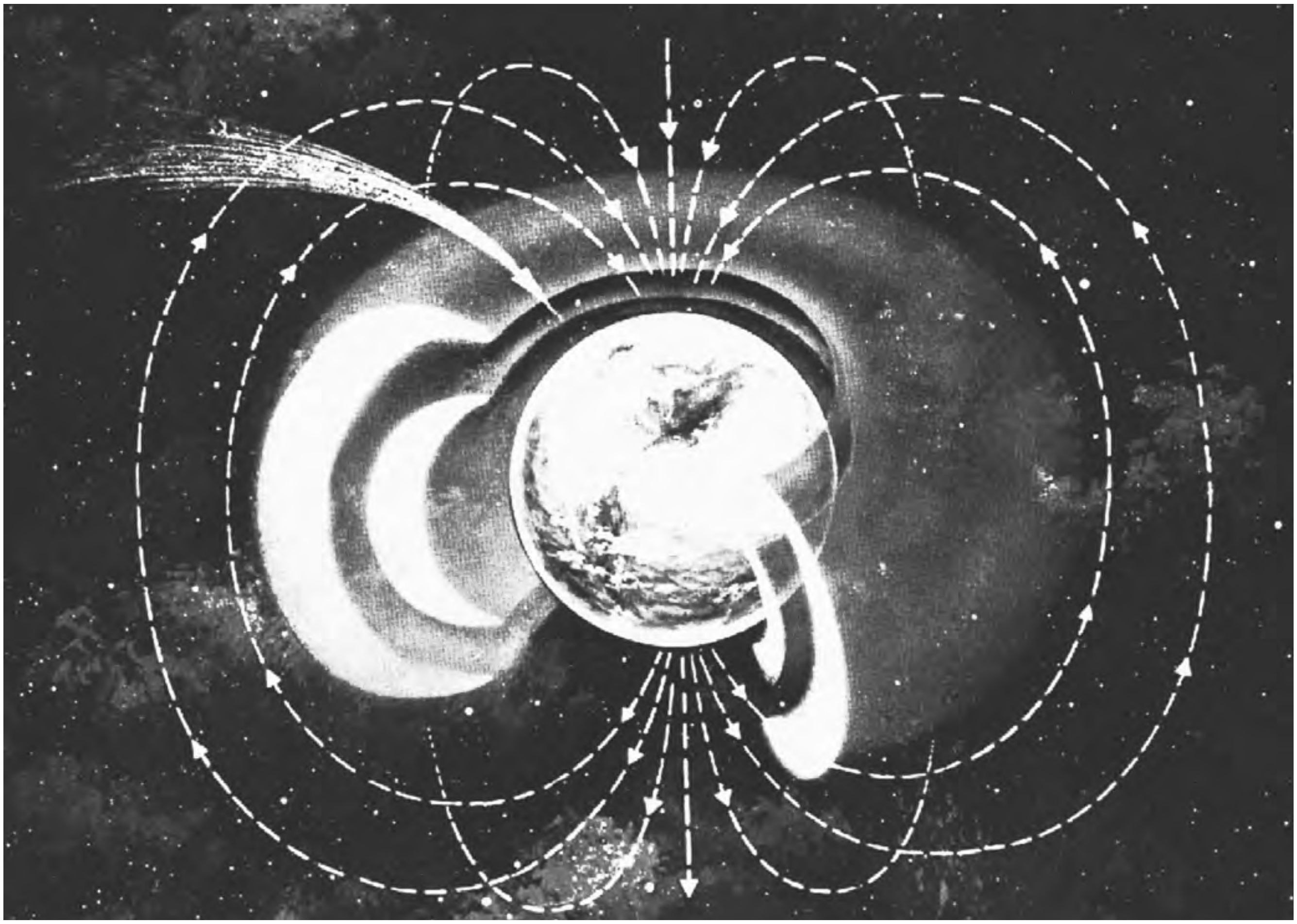
Although fixed by the axis of rotation, the geographic poles undergo slight wobble-like displacements in a circular pattern that shift the poles approximately six meters per year. Located on shifting polar **ice**, the North Pole (geographic pole) is technically defined as that point 90° N **latitude**, 0° longitude (although, because all longitude lines converge at the poles, any value of longitude can be substituted to indicate the same geographic point). The South Pole (geographic pole) is technically defined as that point 90° S latitude, 0° longitude. Early explorers used sextants and took celestial readings to determine the geographic poles. Modern explorers reply on **GPS** coordinates to accurately determine the location of the geographic poles.

Earth's **magnetic field** shifts over time, eventually completely reversing its polarity. There is evidence in magnetic mineral orientation that, during the past 10–15 million years, reversals have occurred as frequently as every quarter million years. Although Earth's magnetic field is subject to constant change (periods of strengthening and weakening) and the last magnetic reversal occurred approximately 750,000 years ago, geophysicists assert that the next reversal will not come within the next few thousand years. The present alignment means that at the northern magnetic pole, a **dip** compass (a compass with a vertical swinging needle) points straight down. At the southern magnetic pole, the dip compass needle would point straight up or away from the southern magnetic pole.

The magnetic poles are not stationary and undergo polar wandering. The north magnetic pole migrates about 6.2 mi (10 km) per year. The magnetic reversals mean that as **igneous rocks** cool from a hot **magma**, those that contain magnetic **minerals** will have those minerals align themselves with the magnetic polarity present at the time of cooling. These volcanic rocks preserve a history of magnetic reversals and when found in equidistant banded patterns on either side of sites of sea floor spreading, provide a powerful paleomagnetic proof of **plate tectonics**.

Navigators using magnetic compass readings must make corrections both for the distance between the geographic poles and the magnetic poles, and for the shifting of the magnetic poles. Moreover, the magnetic poles may undergo displacements of 25–37 mi (40–60 km) from their average or predicted position due to **magnetic storms** or other disturbances of the **ionosphere** and/or Earth's magnetic field. Angular corrections for the difference between the geographic poles and their corresponding magnetic pole are expressed as magnetic declination. The values for magnetic declination vary with the observer's position and are entered into navigation calculations to relate magnetic heading to true directional heading.

See also Bowen's reaction series; Cartography; Continental drift theory; Earth, interior structure; Ferromagnetic; GPS; Magnetic field; Magnetism and magnetic properties; Polar axis and tilt



Earth's magnetic fields and the Van Allen radiation belts. ***U.S. National Aeronautics and Space Administration (NASA).***

GEOGRAPHY • *see* EARTH SCIENCE

GEOLOGIC MAP

A geologic map shows the types of rocks or loose sediments at or below Earth's surface, along with their distribution. Geologic maps also illustrate the relative ages of, and physical relationships between, Earth's materials. Geologic maps are used for a variety of purposes, including natural resource development, land use planning, and natural hazard studies.

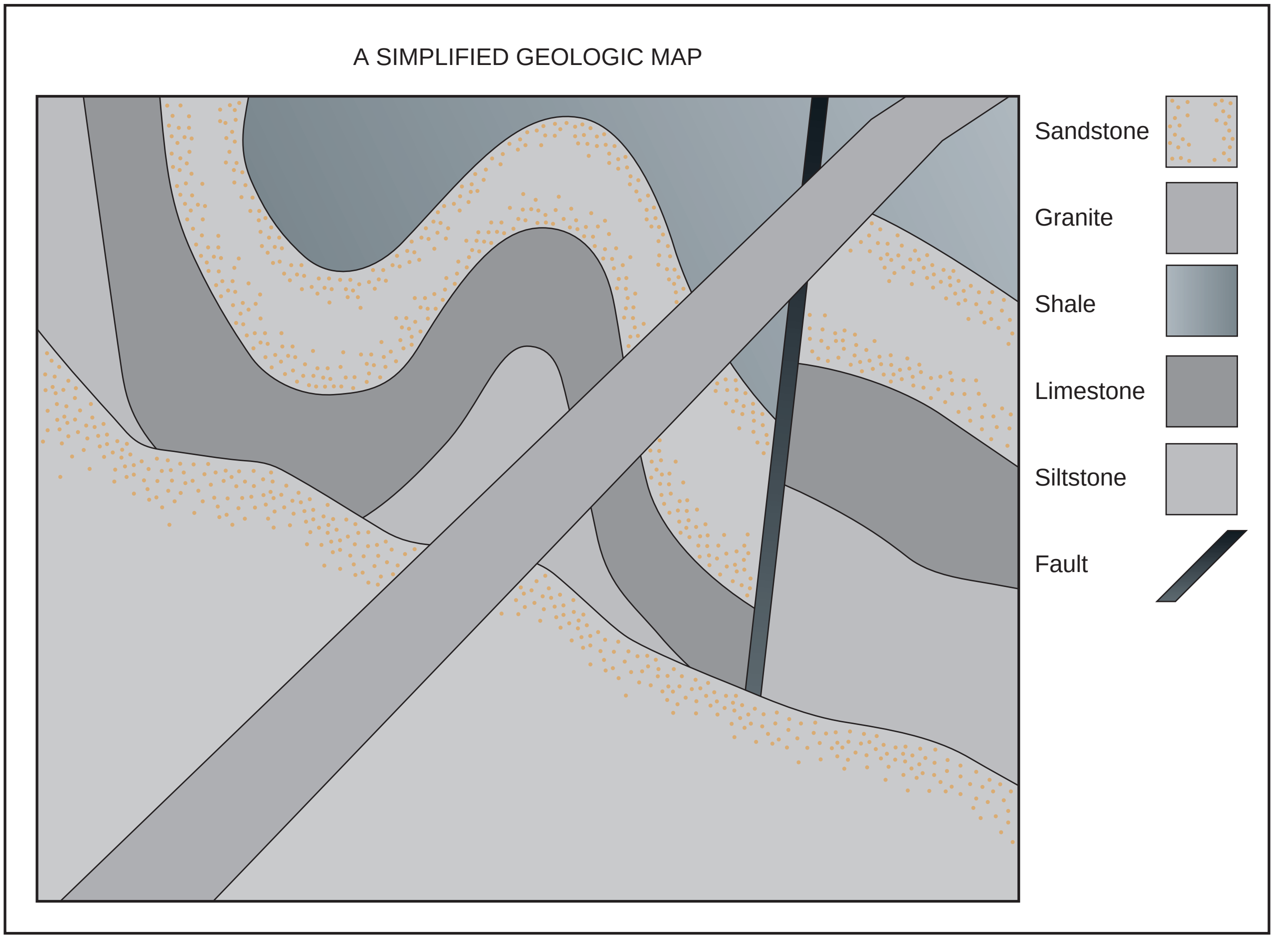
There are three steps to constructing a geologic map. First, the geologist locates natural or man-made exposures of **rock** called outcrops. Second, the geologist records outcrop locations and characteristics on a simple base map. Finally, the geologist prepares a geologic map by interpreting the distribution of and relationships between rock units.

Outcrops provide several kinds of data that are critical to map construction. The geologist records the rock type, for example, **sandstone** or **granite**, and a detailed description of its specific physical characteristics. **Fossils**, if present, may allow the rock to be dated fairly accurately. If more than one rock type is present, the nature of the contact between them is important. In addition, the geologist records the shape and spatial orientation of each rock unit.

The accuracy of a geologic map is primarily dependent upon the spacing of outcrops. If outcrops are widely spaced, the geologist must use his or her knowledge of local and regional **geology** to fill in, or interpolate, between the outcrops. In most cases, the best interpretation will be the simplest one that fits all the known data.

The spacing of outcrops is dependent upon several factors. If the terrain is steep or vegetation is sparse, outcrops are better exposed. Rock units that are resistant to **erosion** also form good outcrops. Finally, in flat terrain, resistant beds are better exposed if they are steeply inclined (due to deformation).

The fundamental rock unit for mapping is the formation. A formation is a body of rock consisting of one or more rock types, usually at least 10 ft (3 m) in thickness, that is present over a large geographic **area**. These characteristics allow it to be the basis for geologic mapping. Formations are named for a geographic location, such as a town, near where



Geologic map.

they were first described. For example, the Miami **Limestone** was named for Miami, Florida.

The distribution of each formation is shown on the map using a separate color, a letter code, or both. A line indicates where the contact is located between adjacent formations. If the contact is exposed at the surface, a solid line is used; if covered, a dashed line is used. Heavier lines indicate the location of faults. With training, one can learn to determine the geologic history of an area from looking at a geologic map.

See also Bathymetric mapping; Cartography

GEOLOGIC TIME

There are several different ways that Earth scientists consider time. Geologic time is generally thought of as the period of time that begins with the initial formative processes of Earth and ends with the onset of recorded human history. The human era begins with the end of geologic time and continues today. Archeologic time, which begins with early hominid **evolution** and also continues through today, overlaps with geologic time. Encompassing all other measures of time is cosmologic time, which begins with the formation of the Universe and will continue until it ends.

In the early days of the Enlightenment era, geologic and cosmologic time were viewed as one, because there was no perceived difference between the age of the earth and the Universe as a whole. **James Hutton** (1726–1795), a founding father of **geology** during this era, stated his view of geologic/cosmologic time thusly: “We find no vestige of a beginning—no prospect of an end.” One of Hutton’s contemporaries, John Playfair (1748–1819), is noted for having said of the well-exposed stratigraphic relations at Siccar Point, Scotland: “The mind seemed to grow giddy by looking so far into the abyss of time.” Then, as today, vast spans of pre-historic time seemed unimaginable. Now we know that there is a difference between geologic and cosmologic time, and appreciate that there was a beginning for Earth—and for the Universe—and that there is a theoretical end for both.

Notions of archaeologic, geologic, and cosmologic time have been rejected and in some instances suppressed by persons who possessed strong beliefs in the concept of Biblical time. Biblical time was the prevailing view of time espoused as a generally unquestioned belief by Christian people for nearly 2,000 years. In 1650–1654, Archbishop James Ussher (1581–1656) of England attempted to quantify Biblical time by studying Biblical genealogies. Based on his analysis, he reckoned that the Earth was formed on October 23, 4004 B.C. This date was printed after 1658 as a footnote in the *English Bible*, and was accepted as a part of scripture. Until the Enlightenment era (c. 1750–1850), any estimate of Earth antiquity that conflicted with Ussher's age was dismissed as inconsistent with scripture. During and after the Enlightenment (and in some quarters still today), resistance persisted to notions of ages that predate the approximate 6,000-year figure of Ussher.

Enlightenment era notions that geologic time was infinite, indefinite, or inconceivably long, would be replaced in time by finite estimates of ages of geological materials. This occurred not long after the nature of radioactive decay was understood and analytical equipment was developed to a level of precision and accuracy in order to measure minute amounts of radioactive isotopes. The advent of this analytic process lead to radiometric dating of **minerals** within rocks using isotopic ratios. For instance, the American chemist Bertram Boltwood (1870–1927) was obtaining **rock** ages, based on lead isotopes, of 410 to 2.2 billion years in the early years of the twentieth century. In 1931, a carefully prepared and highly reviewed report to the United States National Research Council established the validity of radiometric dating of rocks in a robust way that has not been debated since that time. Not long after radiometric dating of rocks began, the geological time scale, which had been only a relative time scale up to that time, became a geochronometric scale as well (i.e., ages of the geologic eras and periods, and eventually their finer subdivisions, were added and refined). For the first time, it was known that, for example, Cretaceous spanned 146.5 to 65 million years ago.

Geologic time for the geologist is the numerical aspect of change in the history of the earth (i.e., the rock record). This differs from other scientific views of time. For example, for the classical physicist, time is more the numerical aspect of motion, because motion is measured by time. Non-scientists normally do not think of time in either of these ways. To the average person, time is the numerical aspect that allows one to order events within a day, a year, or a lifetime or a way to know when to begin or end a task. Thus, the geologic concept of time is rather foreign to most people. Because of its vast dimensions, geologic (and cosmologic) time has the potential to broaden the perspective of anyone who is willing to consider its implications and compare it with human or historic time. Among the many implications of geologic time is the fact that an unlikely or very rare event will become common. Geologic time is vast enough to accommodate, for example, all stages in organic evolution, mass extinctions and biotic recoveries, crustal plate motions and attendant episodes of crustal deformation, and long-term climatic changes.

See also Chronostratigraphy; Fossil record; Historical geology; Radioactivity; Stratigraphy

Geologists from Hawaiian Volcano Observatory studying the crust of a cooled lava flow from Kilauea, Hawaii, Hawaii. © *Roger Ressmeyer/Corbis. Reproduced by permission.*

GEOLOGY

Geology is the study of the earth. Specifically, geologists may study mountains, valleys, plains, sea floors, **minerals**, rocks, **fossils**, and the processes that create and destroy each of these. Geology consists of two broad categories of study. Physical geology studies Earth's materials (**erosion**, volcanism, sediment deposition, etc.) that create and destroy the materials and **landforms**. **Historical geology** explores the development of life by studying fossils (petrified remains of ancient life) and the changes in land (for example, distribution and **latitude**) via rocks. The two categories overlap in their coverage: for example, to examine a fossil without also examining the **rock** that surrounds it tells only part of the preserved organism's history.

Physical geology further divides into more specific branches, each of which deals with its own part of Earth's materials, landforms, and/or processes. **Mineralogy** and petrology investigate the composition and origin of minerals and rocks, respectively. Sedimentologists look at **sedimentary rocks**, products of the accumulation of rock fragments and other loose Earth materials, to determine how and where they formed. Volcanologists tread on live, dormant, and extinct volcanoes checking **lava**, rocks and gases. Seismologists set up instruments to monitor and to predict earthquakes and **volcanic eruptions**. Structural geologists study the ways rock layers bend and break. **Plate tectonics** unifies most aspects of physical geology by demonstrating how and why plates (sections of Earth's outer **crust**) collide and separate and how that movement influences the entire spectrum of geologic events and products.

Fossils are used in historical geology as evidence of the **evolution** of life on Earth. Plate tectonics adds to the story with details of the changing configuration of the continents and **oceans**. For years paleontologists observed that the older the rock layer, the more primitive the fossil organisms found therein, and from those observations developed evolutionary theory. Fossils not only relate evolution, but also speak of the environment in which the organism lived. Corals in rocks at the top of the Grand **Canyon** in Arizona, for example, show a shallow sea flooded the **area** around 290 million years ago. In addition, by determining the ages and types of rocks around the world, geologists piece together continental and oceanic history over the past few billions of years. For example, by matching fossil and tectonic evidence, geologists reconstructed the history and shape of the 200–300 million year-old supercontinent, Pangaea.

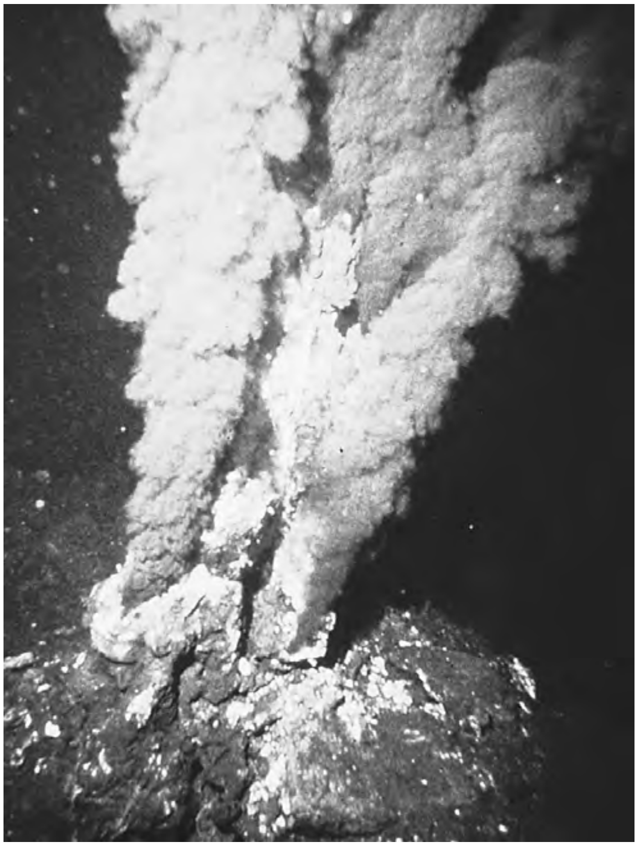
Many other sciences also contribute to geology. The study of the **chemistry** of rocks, minerals, and volcanic gases is known as **geochemistry**. The **physics** of the earth is known as geophysics. Paleobotanists study fossil plants. Paleozoologists reconstruct fossil animals. Paleoclimatologists reconstruct ancient climates.

Much of current geological research focuses on resource utilization. Environmental geologists attempt to minimize human impact on Earth's resources and the impact of natural disasters on human kind. Hydrology and **hydrogeology**, two subdisciplines of environmental geology, deal specifically with **water** resources. Hydrologists study surface water whereas hydrogeologists study ground water. Both disciplines try to minimize the impact of pollution on these resources. Economic geologists focus on finding the minerals and fossil **fuels** (oil, **natural gas**, **coal**) needed to maintain or improve global standards of living. Extraterrestrial geology, a study in its infancy, involves surveying the materials and processes of other planets, trying to unlock the secrets of the universe and even to locate mineral deposits useful to those on Earth.

GEOTHERMAL DEEP-OCEAN VENTS

Geothermal deep-ocean vents are undersea hot **springs** that occur in clusters along the **mid-ocean ridges**. Nutrients and energy supplied by vents support communities of deep-sea organisms found in no other environment.

Most deep-ocean vent action is powered by the heat of the same bodies of **magma** that drive **sea-floor spreading**. A vent forms when seawater seeps downward through cracks in the flanks of a mid-ocean ridge to depths of 1.25–2 mi (2–3 km), about halfway through the thickness of the oceanic **crust**, and is there heated to 750–840°F (400–450°C). This superheated **water** then re-ascends to the center of the mid-ocean ridge and emerges as a fast jet at about 350°C.



Black smoker. ***Photograph by P. Rona. OAR/National Undersea Research Program (NURP)/National Oceanic and Atmospheric Administration.***

As this hot jet mixes with cold (34–36°F [1–2°C]) ocean water, hydrogen sulfide conveyed in solution from the deep rocks precipitates instantly, often coloring the jet black. Such jets are termed "black smokers." Hydrogen sulfide is usually poisonous to life, but the specialized communities around black smokers could not live without it.

A vibrant community of bacteria, tubeworms that are unique to the geothermal vent environment, and other creatures exists around hydrothermal vents. The entire ecosystem is possible because of the activity of the bacteria. These bacteria have been shown, principally through the efforts of the Holger Jannasch (1927–1998) of Woods Hole Oceanographic Institution, to accomplish the conversion of sulfur to energy in a process that does not utilize sunlight called chemosynthesis. The energy is then available for use by the other life forms, which directly utilize the energy, consume the bacteria, or consume the organisms that rely directly on the bacteria for nourishment. For example, the tubeworms have no means with which to take in or process nutrients. Their existence relies entirely on the bacteria that live in their tissues.

Sulfur-oxidizing bacteria pervade the waters around the vents and live symbiotically in the tissues of certain species of animals unique to the vent environment, including 5 ft (2 m) red-blooded worms. These bacteria derive energy by oxidizing the sulfur in hydrogen sulfide, and derive **carbon** from **carbon dioxide** dissolved in the seawater. The bacteria depend directly on the vent and all the other organisms in the vent's vicinity—including over fifty species of clams, mussels, crabs, worms, tube-dwelling worms, and sea anemones not found in any other environment—depend, directly or indirectly, on the bacteria.

Deep-sea vents and their associated fauna were unknown until the late 1970s. They have aroused keen interest for several reasons. First, they demonstrate that life can thrive on energy from purely geothermal sources, isolated from **solar energy**. This suggests the possibility of life in places in the **solar system** where liquid water and heat are available but sunlight is not, such as under the ice-encrusted **oceans** of Jupiter's **moon** Europa. Second, some biologists believe that some vent species are living **fossils** or survivors from earlier periods of **geologic time**. Third, some molecular biologists have theorized that complex chemical reactions in and around ancient deep-sea vents may have synthesized amino acids and other organic molecules key to the spontaneous **origin of life**.

Vents remain an active research topic. In 2001, a new class of deep-sea vents was discovered that derives its energy not from volcanic magma but from a chemical reaction between seawater and the rocks of the upper oceanic crust.

See also Deep sea exploration; Geothermal gradient; Mantle plumes; Ocean trenches

GEOTHERMAL ENERGY

The discovery that the **temperature** in deep mines exceeded the surface temperature implied the existence of a source of deep geothermal energy. Within the continental crusts, the temperature differential gradient averages about one micro calorie per square centimeter (equivalent to an increase of about 95°F per mile or 33°C per kilometer of increasing depth).

In some areas geothermal energy is a viable economic alternative to conventional energy generation. Commercially viable geothermal fields have the same basic structure. The source of heat is generally a magmatic intrusion into Earth's **crust**. The **magma** intrusion generally measures 1110–1650°F (600–900°C), at a depth of 4.3–9.3 mi (7–15 km). The **bedrock** containing the intrusion conducts heat to overlying aquifers (i.e., layers of porous **rock** such as **sandstone** that contain significant amounts of **water**) covered by a dome-shaped layer of impermeable rock such as shale or by an overlying fault thrust that contains the heated water and/or steam. A productive geothermal generally produces about 20 tons (18.1 metric tons) of steam, or several hundred tons of hot water, per hour. Historically, some heavily exploited geothermal fields have had decreasing yields due to a lack of replenishing water in the **aquifer**, rather than to cooling of the bedrock.

There are three general types of geothermal fields: hot water, wet steam, and dry steam. Hot water fields contain reservoirs of water with temperatures between 140–212°F (60–100°C), and are most suitable for space heating and agricultural applications. For hot water fields to be commercially viable, they must contain a large amount of water with a temperature of at least 140°F (60°C) and lie within 2,000 meters of the surface.

Wet steam fields contain water under pressure and usually measure 212°F (100°C). These are the most common commercially exploitable fields. When the water is brought to the surface, some of the water flashes into steam, and the steam may drive turbines that can produce electrical power.

Dry steam fields are geologically similar to wet steam fields, except that superheated steam is extracted from the aquifer. Dry steam fields are relatively uncommon.

Because superheated water explosively transforms into steam when exposed to the atmosphere, it is much safer and generally more economical to use geothermal energy to generate **electricity**, which is much more easily transported. Because of the relatively low temperature of the steam/water, geothermal energy may be converted into electricity with an efficiency of 10–15%, as opposed to 20–25% for **coal** or oil fired generated electricity.

To be commercially viable, geothermal electrical generation plants must be located near a large source of easily accessible geothermal energy. A further complication in the practical utilization of geothermal energy derives from the corrosive properties of most **groundwater** and steam. In fact, prior to 1950, metallurgy was not advanced enough to enable the manufacture of steam turbine blades resistant to **corrosion**. Geothermal energy sources for space heating and agriculture have been used extensively in Iceland, and to some degree Japan, New Zealand, and the former Soviet Union. Other applications include paper manufacturing and water **desalination**.

While geothermal energy is generally presented as non-polluting energy source, water from geothermal fields often contains large amounts of hydrogen sulfide and dissolved **metals**, making its disposal difficult.

See also Earth, interior structure; Energy transformations; Geothermal deep ocean vents; Geothermal gradient; Temperature and temperature scales

GEOTHERMAL GRADIENT

The geothermal gradient is the rate of change of **temperature** (ΔT) with depth (ΔZ), in the earth. Units of measurement are °F/100 ft or °C/km. In the geosciences, the measurement of T is strongly associated with heat flow, Q, by the simple relation: $Q=K\Delta T/\Delta Z$, where K is the thermal conductivity of the **rock**.

Temperatures at the surface of the earth are controlled by the **Sun** and the atmosphere, except for areas such as hot **springs** and **lava** flows. From shallow depths to about 200 ft (61 m) below the surface, the temperature is constant at about 55°F (11°C). In a zone between the near surface and about 400 ft (122 m), the gradient is variable because it is affected by atmospheric changes and circulating ground **water**. Below that zone, temperature almost always increases with depth. However, the rate of increase with depth (geothermal gradient) varies considerably with both tectonic setting and the thermal properties of the rock.

High gradients (up to 11°F/100 ft, or 200°C/km) are observed along the oceanic spreading centers (for example, the Mid-Atlantic Rift) and along **island arcs** (for example, the Aleutian chain). The high rates are due to molten volcanic rock (**magma**) rising to the surface. Low gradients are observed in tectonic subduction zones because of thrusting of cold, water-filled sediments beneath an existing **crust**. The tectonically stable shield areas and sedimentary basins have average gradients that typically vary from 0.82–1.65°F/100 ft (15–30°C/km).

Measurements of thermal gradient data in Japan range widely and over short horizontal distances between to 0.6–4.4°F/100 ft (10–80°C/km). The Japanese Islands are a volcanic island arc that is bordered on the Pacific side by a trench and subduction complex. The distribution of geothermal gradients is consistent with the tectonic settings. In the northeastern part of Japan, the thermal gradient is low on the Pacific side of the arc and high on the back-arc side. The boundary between the outer low thermal gradient and the high thermal gradient regions roughly coincides with the boundary of the volcanic front.

The geothermal gradient is important for the oil, gas, and **geothermal energy** industries. Downhole logging tools must be hardened if they are to function in deep oil and gas wells in areas of high gradient. Calculation of geothermal gradients in the geological past is a critical part of modeling the generation of **hydrocarbons** in sedimentary basins. In Iceland, geothermal energy, the main source of energy, is extracted from those areas with geothermal gradients ≥2.2°F/100 ft (≥40°C/km).

See also Island arcs; Subduction zone; Hydrothermal processes

GESNER, KONRAD VON (1516-1565)

German physician, zoologist, and naturalist

Konrad von Gesner, a dedicated physician by many accounts, somehow managed to produce approximately 90 manuscripts during his short life span. The topics of his publications were encyclopedic in scope and ranged from zoology to theology, mountains to medicines, and to many other subjects that struck his fancy. Of all his works, the one of most interest to geologists is *Fossils, Gems, and Stones* (the full Latin title of this work is *De Rerum Fossilium, Lapid um et Gemmarum maxime, figuris et similitudinibus Liber: non solum Medicis, sed omnibus rerum Naturae ac Philogiae studiosis, utilis et juncundus futurus*). It was published in the year of his death (1565).

Gesner's *Fossils, Stones, and Gems* is significant primarily for two contributions to the study of **fossils**, **minerals**, rocks, and gems. First, although he did not recognize fossils as the remains of once living things (he labeled them stony concretions), Gesner realized that their unusual appearance deserved recognition. Therefore, he assembled the first extensive collection of fossil illustrations. However, he was not the first to publish fossil illustrations, as some historians have suggested; German naturalist Christophorus Encelius (1517–1583) included illustrations of four fossils in a publication 14 years prior to Gesner's work. Gesner's illustrations went far beyond Encelius' work in scope and even included the four illustrations from Encelius' publication.

Second, like his contemporary, German scientist **Georgius Agricola** (1494–1555), Gesner recognized the inadequacy of past methods of classifying fossils, rocks, minerals, and gems which ranged from alphabetical listings to nonsensical mystical properties. Agricola solved the classification problem by carefully identifying physical and chemical properties of certain minerals, a methodology that remains in effect today. Gesner approached the classification problem from a very different perspective. He constructed a list of 15 classes into which he held that most fossils, rocks, minerals, and gems could be categorized.

To the modern geologist, some of these classes may seem trivial or illogical. In class three, for example, fossil Echinoderms, Neolithic stone axes, and minerals that have a smokey appearance are all grouped together as objects that fell from the sky. This class was derived from the teachings of the Greek philosopher Aristotle (384–322 B.C.) and was believed to be the literal truth. Other classes appear to have little value. Class thirteen bears this out by including only fossils, rocks, minerals, and gems that derive their names from birds. A few of Gesner's classes, however, proved valuable to future fossil research. Despite the fact that neither Gesner nor his contemporaries recognized fossils as the remains of living things, he applied his remarkable knowledge of zoology to a practical classification of many fossils. Class 10 (coral in appearance), Class 11 (coral like sea plants in appearance), Class 14 (appearance of things living in the sea), and Class 15 (appearance of insects and serpents) all make this point.

It was not until 136 years after Gesner's death that English naturalist, **John Ray** (1628–1705), declared that fossils were the remains of ancient life and another hundred years before Ray's views were generally accepted. But it was Gesner's early illustrations and some of his methods of classification that highlighted the remarkable similarities between the **fossil record** and living organisms.

Historians have recorded that Konrad von Gesner refused to leave his patients when the plague struck Zürich, Switzerland in 1565. After contracting the disease himself, he asked to be carried to his study when he felt death was near. It was there, among his voluminous library and eclectic collections, that he died.

See also Fossil record; Fossils and fossilization

GEYSER

A geyser is an intermittent spout of geothermally heated **groundwater**. The word *geyser* comes from the name of a single Icelandic geyser, Geysir, written mention of which dates back to A.D. 1294.

Some geysers erupt periodically, others irregularly; a few send jets of **water** and steam hundreds of feet into the air, others only a few feet. There are fewer than 700 geysers in the world, all concentrated in a few dozen fields. More than 60% of the world's geysers are in Yellowstone National Park in the northwestern United States, including the famous geyser, "Old Faithful."

Geysers form only under special conditions. First, a system of underground channels must exist in the form of a vertical neck or series of chambers. The exact arrangement cannot be observed directly, and probably varies from geyser to geyser. This system of channels must vent at the surface. Second, water deep in the system—tens or hundreds of meters underground—must be in contact with or close proximity to **magma**. Third, this water must come in contact with some **rock** rich in silica (**silicon** dioxide, SiO_2), usually **rhyolite**.

Silica dissolves in the hot water and is chemically altered in solution. As this water moves toward the surface, it deposits some of this chemically altered silica on the inner surfaces of the channels through which it flows, coating and sealing them with a form of opal termed *sinter*. Sinter sealing allows water and steam to be forced through the channels at high pressure; otherwise, the pressure would be dissipated through various cracks and side-channels.

The episodic nature of geyser flow also depends on the fact that the boiling point of water is a function of pressure. In a vacuum (zero pressure), liquid water boils at 0°C; under high pressure, water can remain liquid at many hundreds of degrees. Water heated above 100°C but kept liquid by high pressure is said to be *superheated*.

The sequence of events in an erupting geyser follows a repeating sequence. First, groundwater seeps into the geyser's reservoirs (largely emptied by the previous eruption), where it is heated—eventually, superheated—by nearby magma. Steam bubbles then form in the upper part of the system, where the boiling point is lower because the pressure is lower. The steam bubbles eject some water onto the surface and this takes weight off water deeper in the system, rapidly lowering its pressure and therefore its boiling point. Ultimately, the deeper water flashes to steam, forcing a mixed jet of water and steam through the geyser's surface vent.

Many of the world's geysers are endangered by drilling for **geothermal energy** in their vicinity. Drilling draws off water and heat, disrupting the unusual balance of underground conditions that makes a geyser possible.

See also Bedrock; Country rock; Crater, volcanic; Geothermal deep ocean vents; Geothermal gradient; Hotspots; Magma chamber; Pluton and plutonic bodies; Volcanic eruptions; Volcanic vent; Water table

GIS

GIS is the common abbreviation for Geographic Information Systems, a powerful and widely used computer software program that allows scientists to link geographically referenced information related to any number of variables to a map of a geographical **area**.

GIS programs allow scientists to layer information so that different combinations of data plots can be assigned to the same defined area. GIS also allows scientists to manipulate data plots to predict changes or to interpret the **evolution** of historical data.

GIS maps are able to convey the same information as conventional maps, including the locations of **rivers**, roads, topographical features, and geopolitical information (e.g., location of cites, political boundaries, etc.).

In addition to conventional map features, GIS offers geologists, geographers, and other scholars the opportunity to selectively overlay data tied to geographic position. By overlaying different sets of data, scientists can look for points or patterns of correspondence. For example, rainfall data can be layered over another data layer describing terrain features. Over these layers, another layer data representing **soil** contamination data might be used to identify sources of pollution. In many cases, the identification of data correspondence spurs additional study for potential causal relationships.

GIS software data plots (e.g., sets of data describing roads, elevations, stream beds, etc.) are arranged in layers that be selectively turned on or turned off.

In addition to scientific studies, GIS technology is increasingly used in emergency planning and resource management. When tied in with **GPS** data, GIS provides very accurate mapping. GIS provides, for example, powerful data **correlation** between pollution patterns monitored at specific points and wildlife population changes monitored by GPS tracking tags.

Broad in scope, GIS is becoming more widely used in business and marketing studies.

See also Archeological mapping; Area; Cartography

GLACIAL LANDFORMS

Glacial **landforms** are deposits of sediments produced by the advance and retreat of **glaciers**. As a glacier forms and advances, large amounts of **rock** and **soil** are picked up and incorporated into the base of the **ice**. In alpine glaciers, **erosion** along valley walls may also contribute sediment build-up on the top of the glacier. The continual flow of the glacier carries these materials forward until they reach the end of the glacier, where they are deposited when the toe of the glacier melts away. If the sediments are deposited directly from the ice, they are called **till**. Till consists of a range of unconsolidated and usually unstratified materials in a range of sizes, from **clay** to large boulders. Sediments may also be transported and deposited by glacial melt **water** and are termed glaciofluvial deposits.

A distinct deposit of till is called a moraine. Because till is deposited more or less as it is turned out by a glacier, the resulting **moraines** tend to be irregularly and randomly shaped mounds and hills. A variety of moraine types is distinguished.

A moraine that is deposited at the toe of a glacier is an end moraine. Till deposited along the edge of a glacier is a lateral moraine. The furthest extent of a glacier before it retreats is marked by a specific type of end moraine called a terminal moraine. Intermittent halts in glacial retreat may produce recessional moraines.

If a portion of a glacier melts in place, leaving all the accumulated sediment in place, it produces a till plain. Large isolated boulders that have been transported and deposited by glaciers are called erratics.

A glacier can also produce more regularly shaped landforms as well. Eskers are snakelike deposits of **sand** and gravel deposited in ice tunnels at the base of a glacier formed by flowing streams. Because the sediments in an esker were deposited by running water, they tend to be better sorted than till and can be layered. A kettle is a circular depression, often filled by a lake, that is produced when a large block of ice is detached from a glacier and is subsequently surrounded by till. The ice eventually melts, leaving the depression or lake in its place. Drumlins are elongated, asymmetric mounds of till that resemble a teardrop. They are deposited by a retreating continental glacier with the tapered end indicating the direction of retreat. Kames are conical mounds of sediment deposited where a stream exits a glacier. Outwash plains are large areas of well-sorted glaciofluvial sand deposited beyond the end of a glacier by numerous converging streams of meltwater.

See also Glaciation; Ice ages

GLACIATION

Glaciation is an extended period of time during which **glaciers** are present and active. It also refers to all the processes that form glaciers and that are at work within a glacier. A glacier is a land-based mass of highly compacted **ice** that moves downward and outward under its own weight due to **gravity**. Glaciers may be large enough to cover a continent or small enough to fill a mountain valley and periods of glaciation can last hundreds, thousands, or millions of years.

A glacier is formed by a series of processes that begins with accumulation. Accumulation occurs when the buildup of snow and ice through snowfall, avalanching, or **wind** transport during cold months greatly exceeds the loss through **melting** or sublimation (the direct conversion of a solid to a gas) in warmer months. As snow accumulates and deepens, its weight causes increased pressure that converts snowflakes first into granular snow and eventually into dense ice granules. Continual and sustained accumulation, compaction, melting, and refreezing eventually create a very dense mass of interlocking ice with about 10% void space. As a comparison, freshly fallen snow contains about 80% void space. The formation of new glacial ice takes several decades.

A mass of accumulated snow and ice is not strictly considered a glacier until it begins to move downhill. Glacial ice will begin to move when it becomes too thick and heavy to hold its position against gravity. The instant that glacial ice will begin to move depends on the steepness of the ground, the ice thickness, and the ice **temperature**. In mountainous regions a glacier will start to **creep** when it reaches a thickness of 65.5–131 ft (20–40 m). Glaciers usually move very slowly, less than one meter a day, but can move up to 164 ft (50 m) a day.

Although a glacier is constantly creeping downhill, the front edge of it may appear to remain in the same place, or even retreat uphill. This is because at the same time a glacier is moving, it may be growing or shrinking. A glacier fluctuates depending on the rate of the accumulation of new ice versus the rate of ablation, or the loss of ice due to melting, sublimation, and wind **erosion**. A glacier will appear to advance if accumulation exceeds ablation and it will recede if ablation is greater than accumulation. If the two are equal, the glacier will appear to remain stationary. When a glacier advances far enough to reach a body of **water**, large chunks may break off and fall in into the water. This is called calving and is the source of **icebergs**.

Throughout **geologic time**, Earth has experienced major periods of glaciation when glaciers covered large portions of Earth's surface for up to many millions of years. In the last 500,000 years, four major periods of glaciation have occurred. During these times, ice sheets several kilometers thick covered as much as 30% of the global land surface. This type of glaciation, which extends over vast areas of lowlands and mountains, is known as continental glaciation. The most recent major glaciation ended about 10,000 years ago.

Today, continental glaciation occurs only at the polar regions, mostly in Greenland and **Antarctica**. Active glaciation in other parts of the world exists in mountainous regions at high altitudes and is called alpine glaciation. The causes of glaciation are not completely understood, but major periods of glaciation are attributed to decreases in the amount of sunlight the earth receives due to very long-term cyclic variations in Earth's **rotation** and angle of orbit.

See also Glacial Landforms

GLACIERS

Glaciers are large land-bound bodies of **ice**. To be called a glacier, the ice mass must be moving, or show evidence of having moved in the past. Covering about 10% of Earth's surface, glaciers store a significant amount of Earth's supply of **freshwater**.

Glaciers form from the buildup of snow over time. As snow accumulates, it is compressed under its own weight. Compaction, along with partial thawing and refreezing, converts the original snow to a type of granular ice called firn. As snow continues to accumulate, the firn is buried and further compacted and is eventually converted into glacial ice. Sufficient accumulation of snow and ice is critical to the ability of glacial ice to deform and flow. Pressure from above allows the solid ice to flow at depth.

Glacial ice flows outward from the center of the accumulation and/or downhill under the force of **gravity**. Plastic flow, the chief mechanism of glacial movement, occurs when individual ice **crystals** within the center of the mass move very small distances. The cumulative motion of a large number of

Glacier, Muir Bay Inlet, Glacier Bay National Park, Alaska. ***JLM Visuals. Reproduced by permission.***

ice crystals results in movement of the glacier as a whole. Basal slip is another important mechanism of glacial flow. It occurs when the glacier slides along its base, usually aided by the presence of meltwater between the ice and the land surface. Glacial movement is generally so slow as to be imperceptible to the human eye. Rates of movement typically range from a few millimeters to a few meters per day. Occasionally, however, a glacier may surge, moving tens of meters per day for a period of months to years, before slowing down again.

The two main types of glaciers, classified based on size and location, are continental and alpine glaciers. A continental glacier, as the name suggests, is one that covers a large portion of a continent. These glaciers, also known as ice sheets, flow out from one or more centers of accumulation. Such zones of accumulation are typically more than 1.9 mi (3 km) thick, and continental glaciers cover most of the region's topographical features except for the highest mountain peaks. Continental glaciers are presently found only in Greenland and **Antarctica**. Over 695,000 mi^2 (1,800,000 km^2) of Greenland is hidden beneath its ice sheet, while continental glaciers in Antarctica cover 4,885,350 mi^2 (12,653,000 km^2). During the Pleistocene, continental glaciers were widespread, and massive ice sheets covered much of **North America**. Depositional and erosional evidence of their existence can be found throughout Canada and the northern portion of the United States. Smaller versions of continental glaciers, known as ice caps, cover less than 19,300 mi^2 (50,000 km^2). The small continental glacier covering much of Iceland is an example of an ice cap. Ice caps are also found in the polar regions of Canada, including Baffin Island.

Alpine glaciers are those that occur in mountainous regions. Alpine glaciers are much smaller than continental glaciers, and flow from areas of higher elevation to lower areas. Large alpine glaciers in North America occur in Alaska and the Rocky Mountains. As alpine glaciers flow down from mountaintops, they are generally confined to a valley or system of valleys. These valley glaciers are analogous to streams, and often have smaller tributary glaciers that flow into them. Valley glaciers leave behind clear evidence of their existence. River **erosion** typically produces a valley that is narrow at the bottom, with a V-shaped cross section. Wide, flat-floored valleys with a U-shaped cross section indicate the previous existence of a valley glacier. Matanuska Glacier, located along the highway 90 mi (145 km) northeast of Anchorage, Alaska, is a famous example of a valley glacier.

Glaciers are responsible for reshaping the land by eroding and transporting a great deal of material. Glaciers erode material by plucking and abrasion. Plucking refers to the removal of **rock** by the advancing ice. Material may be plucked from beneath or along the sides of a glacier, and then picked up and transported by the moving ice mass. Abrasion differs from plucking in that it doesn't involve removing large particles of rock; rather it refers to grinding or filing processes. Highly polished rock surfaces are formed by abrasion. Where large rock fragments are embedded into the bottom of the ice, they may grind into the underlying **bedrock** forming glacial striations, or scratches. The Pleistocene glaciers formed in Canada and the northern United States have left behind large areas of polished and striated bedrock, exposed when glaciers scraped off the surface sediment. Other erosional features of glaciers include hanging valleys, cirques, arêtes, and horns.

Glaciers eventually deposit the material they accumulate. Material deposited by glaciers includes glacial erratics, large boulders transported by ice and deposited far from their source; glacial **till**, unsorted deposits of sediment and rocks; and stratified drift, layered, sorted deposits that originated from glacial streams. Extensive deposits of sediment from glacial streams are known as outwash plains. Depositional **landforms** created by glaciers include **moraines**, drumlins, kanes, and eskers.

See also Glacial landforms; Glaciation; Polar Ice

GLASS

Although a glass is a substance that is non-crystalline, it is almost completely undeformable and therefore brittle. A glass exists in a state of matter termed a vitreous state. Vitreous substances, when heated, will transform slowly through stages of decreasing viscosity. As a sample of glass is heated, it becomes increasingly deformable, eventually reaching a point where it resembles a very viscous liquid. **Ice**, on the other hand, does not go through these changes as it is heated.

Excepting sublimation (direct solid to gas transformations) most substances change directly from a solid to a liquid. Ice, therefore, is not a vitreous substance. Glasses are only very slightly deformable. Glasses tend to bend and elongate under their own weight, especially when formed into rods, plates, or sheets. Glasses can be either organic or inorganic materials.

Because solidification is the act of crystallization, the depiction of glass as a non-crystalline solid may not be entirely correct. However, true crystallization occurs when the molecules of a substance arrange themselves in a systematic, periodic fashion. The atoms or molecules of glass do not exhibit this periodicity; this is consistent with the depiction of glass as an extremely viscous, or “supercooled”’ liquid.

Glass is often referred to as an **amorphous** solid. An amorphous solid has a definite shape without the geometric regularity of crystalline solids. Glass can be molded into any shape. If glass is shattered, the resulting pieces are irregularly shaped. A crystalline solid would exhibit regular geometrical shapes when shattered. Amorphous solids tend to hold their shape, but they also tend to flow very slowly. If left undisturbed for a long period of time, a glass will very slowly crystallize. Once it crystallizes, it is no longer considered to be glass. At this point, it has devitrified. This crystallization process is extremely slow and in many cases may never occur.

The chemical make-up of standard window glass, which will be described in greater detail below, is quite similar to the mineral **quartz**. An x-ray crystallographic picture of quartz would show atoms arranged in an orderly, periodic sequence. X-ray crystallography studies of glass show no such arrangement. The atoms in glass are disordered and show no periodic structure. This irregular arrangement of atoms not only defines a substance as glass, but also determines several of its properties.

The bonds between the molecules or ions in a glass are of varying length, which is why they show no symmetry or periodic structure. Because the bonds are not symmetrical, glass is isotropic and has no definite **melting** point. The melting of glass instead takes place over a wide **temperature** range. Changing the state of a substance with asymmetric bonds requires more energy than a crystalline structure would. The tendency of glass to devitrify is a result of the atoms moving from a higher to a lower energy state.

The most common glasses are **silicon** based. Most glasses are 75% silicate. These glasses are based on the SiO_2 molecule. This molecule creates an asymmetric, aperiodic structure. Some of the **oxygen** atoms are not bridged together, creating ions that need to be neutralized by metal cations. These metal cations are randomly scattered throughout the glass structure, adding to the asymmetry. The oxides of elements other than silicon can also form glasses. These other oxides include Al_2O_3, B_2O_3, P_2O_5, and As_2O_5.

The production of glasses is a complicated process. In general, certain molten materials are cooled in a specific manner so that no crystallization occurs, i.e., they remain amorphous. There are four basic materials that are used in glass production. These materials are the glass-forming substances, fluxes, stabilizers, and secondary components.

A glass-forming substance is any mineral that remains vitreous when cooled. Glass-forming substances are usually silica, boric oxide, phosphorous pentoxide, or feldspars. Sometimes **aluminum** oxide (Al_2O_3) is used. Silica, as the most commonly used material to make glass, is usually obtained from **sand**, which is 99.1-99.7% SiO_2. Occasionally, natural silica deposits are discovered that are pure enough to use in glass manufacturing, but these deposits are rare and the silica found in them is usually expensive to obtain. Even the lowest quality sands can be purified rather economically. Impurities in the natural silica are important because they can dramatically alter the quality of the glass produced. The most common impurities found in natural silica are **iron** sesquioxide (Fe_2O_3), alumina (Al_2O_3), and calcium compounds. Ferric oxide is sometimes found as an impurity. Even if the amount of ferric oxide in a natural silica sample is only 0.1% of the sample, the glass produced would have a deep yellow-green color and the impurity would have detrimental effects on the thermal and mechanical properties of the glass.

Occasionally impurities are added to the glass-forming substances to give the glass certain qualities such as transparency, fusibility, or stability. Stabilizers also are used to give the finished product particular characteristics. For example, calcium carbonate can be added as a stabilizer that will make the glass produced insoluble in **water**. **Lead** oxide added as a stabilizer gives the glass extreme transparency, brightness, and a high refractive index. Lead oxide also makes glass easier to cut. Zinc oxide can be added to glass to make it more resistant to changes in temperature as well as to increase its refractive index (a measure of the ability to bend light). Aluminum oxide can also be added as a stabilizer to increase the physical strength of the glass. Secondary components are added to determine some of the final properties of the glass and to correct any defects in the glass. The secondary components can be classified as decolorants, opacifiers, colorants, or refiners.

The production of glass includes many steps that can be generalized as follows. First, the fluxes, glass-forming substances, and stabilizers are crushed and milled, then blended and mixed together. They are then re-milled and granulated. At this point, the secondary components are added, if needed. The granules are then fused, refined, homogenized, and corrected, using more secondary components if necessary. Finally, the glass is formed and finished.

The final product is one of many hundreds of different types of glass. One popular type of glass, especially in laboratory settings or for use in the kitchen, is borosilicate glass. Some well-known borosilicate glasses are Jena, Pyrex, Durax, and Thermoglass. These glasses contain 12% or more B_2O_3. The addition of the boron oxide increases the softening temperature of the glass, making it more resistant to high temperatures such as those experienced while cooking or while performing laboratory experiments. Borosilicate glasses are also used in the production of thermometers, television tubes, and other objects that need to have constant dimensions or a high softening point.

See also Chemical bonds and physical properties

GLENN JR., JOHN H. (1921-)

American astronaut and senator

John H. Glenn Jr. was the first American to orbit the earth. In the wake of this 1962 feat, Glenn became a national hero on the order of Trans-Atlantic aviator Charles A. Lindbergh—a status that helped carry him to a second career in the United States Senate. As a 77-year-old, he made history again when he became the oldest American to travel in **space** on Oct. 29, 1998, aboard the **space shuttle** *Discovery*. His mission was a series of experiments on aging.

John Glenn. ***U.S. National Aeronautics and Space Administration (NASA).***

John Herschel Glenn Jr. was born in Cambridge, Ohio, and grew up in nearby New Concord. He was the son of plumber John Herschel Glenn and Clara Sproat. Glenn credits his parents with instilling his deep-rooted Presbyterian faith and the accompanying philosophy that everyone is given certain talents and a duty to use them to the fullest. In high school Glenn was a diligent student who earned top grades. He worked hard athletically as well, lettering in three sports. After high school Glenn entered Muskingum College in New Concord, majoring in **chemistry**. His high school sweetheart, Anna Castor, enrolled as well.

After two and a half years of study, Glenn entered a local civilian pilot training program and learned to fly. He then left college to enter the Naval Aviation Cadet Program. In 1943, he was graduated and commissioned as a lieutenant in the Marine Corps. He married Annie before going on to advanced training and assignment to a combat unit, and the couple eventually had children. Glenn flew F4U Corsair fighter-bombers on 59 missions in the Pacific theater during World War II.

When peace came, Glenn remained in the corps, serving as a fighter pilot and then as a flight instructor. In 1952, Major Glenn was sent to Korea. He flew primarily ground-attack missions in that war as well, repeatedly returning in aircraft riddled with bullet and shrapnel holes. Through an interservice exchange program, Glenn transferred to an Air Force squadron just before the end of the war. Flying the F–86 Sabre, Glenn downed three North Korean MiG fighters in nine days.

Following Korea, Glenn attended the Naval Test Pilot School, part of the Naval Test Center in Patuxent River, Maryland. After graduating as a test pilot, he spent two years as a project officer evaluating new aircraft. Glenn moved on to the Navy Bureau of Aeronautics in Washington, D.C., where he continued to oversee development of new fighters. These included the F8U Crusader, a plane Glenn made famous in 1957. In Project Bullet, a test Glenn conceived himself, he flew a Crusader coast to coast, making the first transcontinental supersonic flight in a record time of three hours and twenty-three minutes.

When Glenn learned of the upcoming astronaut program, he was captivated by the challenge of spaceflight. He immediately began to strengthen his qualifications, improving his physical condition, volunteering for centrifuge tests and other research projects, and pursuing courses at the University of Maryland. (Glenn did not actually receive a college degree until after he had flown in space, when Muskingum College awarded him a bachelor’s degree in mathematics.) In April 1959, the newly promoted Lieutenant Colonel Glenn was selected as one of America’s seven Mercury astronauts.

Glenn helped design the cockpit layout and instrumentation of the *Mercury* capsule. He became the unofficial spokesperson for the astronaut team, and it was a surprise to the country and to Glenn when fellow astronaut **Alan B. Shepard**, Jr., a lieutenant commander with the U.S. Navy, was chosen to make the first U.S. spaceflight. Shepard and then Gus Grissom, an Air Force captain and astronaut, made suborbital flights, in which the *Mercury* craft was launched by a Redstone rocket. These efforts were eclipsed in the popular imagination by the Soviet Union’s successful orbital manned flights, and the pressure was on the National Aeronautics and Space Administration (NASA) to match the Russian feat as soon as possible. Glenn was chosen to make the first orbital effort, officially known as *Mercury-Atlas 6*.

After several frustrating postponements caused by unsuitable **weather** and technical glitches, Glenn’s capsule, *Friendship 7*, roared into orbit on February 20, 1962. The astronaut fed ground controllers a constant stream of observations and physiological reports, performing experiments such as pulling on an elastic cord to determine the effects of physical work in weightlessness. Tremendous publicity surrounded the flight, in contrast to the secretive Russian launches. Not publicized at the time, however, was a telemetry signal’s indication that Glenn’s heat shield, vital for safe reentry to the earth’s atmosphere, might not be secured to the capsule. Glenn was directed to change the original plan of jettisoning his retro-rocket package after it had been used to slow the capsule; instead it would be kept in place, strapped over the heat shield, to keep the shield from coming loose.

Glenn was briefed on the problem. (He later argued that NASA policy should be to notify airborne astronauts as soon as any abnormality is detected.) Glenn left the retropack on and took manual control of his craft, guiding the capsule to a perfectly safe reentry after three orbits of the earth. It was later determined that the telemetry signal was false, but the incident solidified Glenn's view that spacecraft needed humans aboard who could respond to the unexpected.

Glenn was bathed in national attention. President John F. Kennedy awarded him the NASA Distinguished Service Medal. He was invited to address a joint session of Congress, an honor normally reserved for top officials and visiting heads of state. Glenn told the assembly that the real benefits of space exploration were "probably not even known to man today. But exploration and the pursuit of knowledge have always paid dividends in the long run—usually far greater than anything expected at the outset."

Glenn received hundreds of thousands of letters, some of which he collected in a book, *Letters to John Glenn*. Glenn also became friends with President Kennedy and his brother, U.S. Attorney General Robert Kennedy. The president urged Glenn to enter politics and, unknown to the astronaut, directed that Glenn's life not be risked by another spaceflight. Glenn worked on the preliminary designs for Project Apollo, which had the goal of putting a man on the **Moon**, then left NASA and applied for military retirement to enter the Ohio Senate race in 1964. He withdrew from that contest after suffering a serious head injury in a bathroom fall.

Colonel Glenn retired from the Marines on January 1, 1965, with six Distinguished Flying Crosses and eighteen Air Medals, among other decorations. He had logged over 5,400 hours of flying time. Glenn's space exploit also garnered him numerous civilian honors, including induction into the Aviation Hall of Fame and the National Space Hall of Fame, and, in 1978, the award of the Congressional Space Medal of Honor. He was granted honorary doctorates in engineering by four universities.

After retiring from the military, Glenn went into business, first with the Royal Crown cola company and later with a management group that operated Holiday Inn hotels. His business ventures made Glenn a millionaire, but his political dreams remained foremost in his mind. In 1970, Glenn again declared his candidacy for the U.S. Senate. He narrowly lost in the Democratic primary to Howard Metzenbaum, who outspent and out-organized his less experienced rival. When another Senate seat opened in 1974, Glenn started earlier, ran harder, and won the election.

Despite being new to Washington politics, Glenn gained a reputation for hard work and effective legislating. His voting record marked him as generally liberal on both domestic and foreign policy. Glenn was considered for the vice presidency by presidential nominee Jimmy Carter, but Walter Mondale, a Minnesota senator, was chosen instead. In the Senate, Glenn became best known for his work against nuclear proliferation. He was willing to oppose President Carter on some issues, most notably the second Strategic Arms Limitation Talks (SALT II) arms accord, which Glenn considered unverifiable. He sought the Democratic presidential nomination in 1984; once again, however, Mondale grasped the prize Glenn sought, eliminating Glenn before the party's convention with a better-run campaign. Glenn then served as chair of the Senate Governmental Affairs Committee from 1987 to 1995.

Glenn continued serving in the Senate, where he supported increased funding for education, space exploration, and basic scientific research. He was a strong advocate of a permanent research station in space. Outside the Senate, Glenn served on the National Space Society's Board of Governors, on Ohio's Democratic Party State Executive Committee, and as a Presbyterian elder, among many other commitments.

But not satisfied with his political career and longing to return to space, Glenn asked NASA if he could fly again, but only if he met the agency's physical and mental requirements. On January 16, 1998, NASA announced that Glenn, who had made history 36 years before as the first American to orbit the earth, would fly in space again as a payload specialist on shuttle mission STS-95 October 29. Glenn took part in experiments to study the connection between the adaptation to weightlessness and the aging process. The highly successful mission concluded with the landing on Saturday, November 7, 1998. While he tolerated space flight surprisingly well, Glenn confirmed it was unlikely that he would ever fly in space again.

See also Spacecraft, manned

GLOBAL WARMING

Global warming, as used in the popular context, is a scientifically controversial phenomenon that attributes an increase in the average annual surface **temperature** of Earth to increased atmospheric concentrations of **carbon dioxide** and other gases. Global warming describes only one of several components involved in **climate** change and specifically refers to a warming of Earth's surface outside of the range of normal fluctuations that have occurred throughout Earth's history.

Climate describes the long-term meteorological conditions or average **weather** for a region. Throughout Earth's history there have been dramatic and cyclic changes in climatic weather patterns corresponding to cycles of glacial advance and retreat that occur on the scale of 100,000 years. Within these larger cycles are shorter duration warming and cooling trends that last from 20,000 to 40,000 years. Scientists estimate that approximately 10,000 years have elapsed since the end of the last **ice** age, and examination of physical and biological processes establishes that since the end of the last ice age there have been fluctuating periods of global warming and cooling.

Measurements made of **weather and climate** trends during the last decades of the twentieth century raised concern that global temperatures are rising not in response to natural cyclic fluctuations, but rather in response to increasing concentrations of atmospheric gases that are critical to the natural and life-enabling **greenhouse effect** (infrared re-radiation, mostly from **water** vapor and **clouds**, that warms the earth's surface).

Observations collected over the last century indicate that the average land surface temperature increased by 0.8–1.0°F (0.45–0.6°C). The effects of temperature increase, however, cannot be fully isolated and many meteorological models suggest that such increases temperatures also result in increased **precipitation** and rising sea levels.

Measurements and estimates of global precipitation indicate that precipitation over the world's landmasses has increased by approximately 1% during the twentieth century. Further, as predicted by many global warming models, the increases in precipitation were not uniform. High **latitude** regions tended to experience greater increases in precipitation while precipitation declined in tropical areas.

Measurements and estimates of sea level show increases of 6–8 in (15–20 cm) during the twentieth century. Geologists and meteorologists estimate that approximately 25% of the sea level rise resulted from the **melting** of mountain **glaciers**. The remainder of the rise can be accounted for by the expansion of ocean water in response to higher atmospheric temperatures.

Many scientists express concern that the measured increases in global temperature are not natural cyclic fluctuations, but rather reflect human alteration of the natural phenomena known as the greenhouse effect by increasing concentrations of greenhouse-related atmospheric gases. Estimates of atmospheric **greenhouse gases** prior to the nineteenth century (extrapolated from measurements involving ice cores) indicate that of the last few million years the concentration of greenhouse gases remained relatively unchanged prior to the European and American industrial revolutions. During the last two centuries, however, increased emissions from internal combustion engines and the use of certain chemicals have measurably increased concentrations of greenhouse gases that might result in an abnormal amount of global warming.

Although most greenhouse gases occur naturally, the **evolution** of an industrial civilization has significantly increased levels of these naturally occurring gases. In addition, new gases have been put into the atmosphere that potentiate (i.e., increase) the greenhouse effect. Important greenhouse gases in the modern Earth atmosphere include water vapor and **carbon** dioxide, methane, nitrous oxides, **ozone**, halogens (bromine, chlorine, and fluorine), halocarbons, and other trace gases.

The sources of the greenhouse gases are both natural and man-made. For example, ozone is a naturally occurring greenhouse gas found in the atmosphere. Ozone is constantly produced and broken down in natural atmospheric processes. In contrast, halocarbons enter the atmosphere primarily as the result of human use of products such as chlorofluorocarbons (CFCs). Water vapor and carbon dioxide are natural components of respiration, transpiration, **evaporation** and decay processes. Carbon dioxide is also a by-product of combustion. Although occurring at lower levels than water vapor or carbon dioxide, methane is also a potent greenhouse gas. Nitrous oxides, enhanced by the use of nitrogen fertilizers, nylon production, and the combustion of organic material, including fossil **fuels** have also been identified as contributing to strong greenhouse effects.

Alterations in the concentrations of greenhouse gases results in a disruption of equilibrium processes. Both increased formation and retardation of destruction cause compensatory mechanisms to fail and result in an increased or potentiated greenhouse effect. For example, the amount of water vapor released through evaporation increases directly with increases in the surface temperature of Earth. Within normal limits, increased levels of water vapor are usually controlled by increased warming and precipitation. Likewise, within normal limits, concentrations of carbon dioxide and methane are usually maintained with specified limits by a variety of physical and chemical processes.

Measurements made late in the twentieth century showed that since 1800, methane concentrations have doubled and carbon dioxide concentrations measured at he highest values estimated to have existed during the last 160,000 years. In fact, increases in carbon dioxide over the last 200 years were exponential up until 1973 (the rate of increase has since slowed).

Although the effects of these increases in global greenhouse gases are debated among scientists, the correlation of the increased levels of greenhouse gases with a measured increase in global temperature during the twentieth century, have strengthened the arguments of models that predict pronounced global warming over the next few centuries. In the alternative, some scientists remain skeptical because the earth has not actually responded to the same extent as predicted by these models. For example, where many models based upon the rate of change of greenhouse gases predicted a global warming of .8°F to 2.5°F (0.44°C to 1.39°C) over the last century, the actual measured increase is significantly less with a mean increase generally measured at .9°F (.5°C) and that this amount of global warming is within the natural variation of global temperatures.

One problem in reaching a scientific consensus regarding global warming is that the data used in many models is neither global nor a result of high-reliance systematic scientific measurement (i.e., that it generally neglects **oceans** and vast uninhabited areas). Other problems involve forming an accurate articulation of the interplay of global surface warming phenomena that include thermal conduction, greenhouse radiation, and convective currents. Most scientists agree, however, that an enhanced greenhouse effect will result in some degree of global warming.

See also Acid rain; Atmospheric pollution

GNEISS

Gneiss (pronounced "nice") is a **metamorphic rock** consisting mostly of **quartz** and **feldspar** and showing distinct layering or banding. The layering of a gneiss may be weak or well-developed and consists of varying concentrations of biotite, garnet, hornblende, mica, and other **minerals**. These structures do not record a layered deposition process but arise from preferential recrystallization along flow or stress lines during metamorphosis of the parent **rock** (protolith).

The gneisses are a very varied group, including both **igneous rocks** and metamorphosed **sedimentary rocks**, and may be categorized as quartzofeldspathic, pelitic, calcarous, or hornblende gneiss.

Quartzofeldspathic gneiss forms by metamorphosis of either **silicic** igneous rocks such as **granite**, **rhyolite**, and rhyolitic tuff—or silicic sedimentary rocks such as **sandstone**. Quartzofeldspathic gneiss containing eye-shaped feldspar **crystals** is termed augen gneiss after the German *augen* (eyes).

Pelitic gneiss is formed by metamorphosis of clay-textured sedimentary rocks, particularly those rich in **iron**.

Calcareous gneiss contains calcite ($CaCO_3$). It is formed by metamorphosis of limestones and dolomites containing large fractions of **sand** and **clay**. Calcareous gneisses with large fractions of calcite blur conceptually with the marbles (metamorphosed limestones).

Hornblende gneiss contains a large fraction of hornblende in addition to its quartz and feldspar.

The gneisses can be alternatively categorized simply as orthogneisses and paragneisses. The former are metamorphosed from igneous protoliths and the latter from sedimentary protoliths.

The gneisses and schists are closely related. Both are metamorphosed igneous or sedimentary rocks showing foliation or layering. The difference is primarily one of degree; schists are less coarsely crystallized and more prone to cleave into flakes or slabs. Gneisses represent a higher grade of metamorphosis—more thorough melting—and are distinguished by their coarser texture and their resistance to cleavage.

See also Migmatite

GODDARD, ROBERT H. (1882-1945)

American physicist

Robert H. Goddard was foremost among the first generation of rocket and **space** pioneers. Goddard not only contributed to space flight theory, but also engaged over most of his adult life in the actual development of rockets. As a result, he is credited with launching the world's first liquid-propellant rocket. He developed and patented a large number of innovations in rocket technology that were later used in the much larger rockets and missiles employed by the Germans during World War II and, thereafter, by the United States' and Soviet Union's missile and space programs, among others. Paradoxically, Goddard's influence upon modern rocketry was not as great as it would have been had he been less a solitary inventor and more inclined to publish his findings in scientific journals and elsewhere.

Robert Hutchings Goddard was born in Worcester, Massachusetts, to Nahum Danford Goddard, himself something of an inventor, and Fannie Louise Hoyt Goddard, the daughter of a machine knife manufacturer for whom her husband worked at the time of their marriage. Of modest means but old New England stock, Goddard's parents had a second son who died in infancy. Goddard himself was prone to illness and fell behind in school, compensating with self-education. Encouraged by his father in his early inclinations towards experimentation and invention, Goddard also heeded his father's advice to mind his own business and work for himself rather than someone else. Science fiction proved another early influence upon him, one that apparently led to a transforming experience he had in a cherry tree on October 19, 1899, when he imagined a device that might ascend to Mars. As he stated in an autobiographical memoir, the experience suddenly made life seem purposeful to him. Throughout the rest of his life, he recorded the date in his diary as "anniversary day," and he revisited the tree on that date whenever he was in Worcester.

Robert Goddard. ***U.S. National Aeronautics and Space Administration (NASA).***

Goddard received his early education in the Boston **area**, where his father had been working, and had not done well in algebra during his first year in high school. When the family moved back to Worcester in 1898, after his mother was diagnosed with tuberculosis, his experience in the cherry tree compelled him to excel in math and **physics** at South High School. Because of his own illnesses, Goddard did not graduate from South High until 1904, when he was 21. He went on to earn a bachelor's degree in general science, with a concentration in physics, from Worcester Polytechnic Institute in 1908, and a master's degree from Clark University in 1910. By 1909, Goddard had already begun teaching physics at Worcester Polytechnic and shortly after receiving his doctorate from Clark in 1911, he became an honorary fellow in physics there. Working as a research instructor in physics at Princeton University, Goddard fell dangerously ill in 1913 and, like his mother, was diagnosed with tuberculosis. Initially given only two weeks to live, he recovered sufficiently the following year to become a physics instructor at Clark, where he was promoted to assistant professor in 1915. Goddard would remain at Clark throughout much of his academic career, allowing for leaves of absence to pursue rocket research. Goddard eventually became head of Clark's physics department and director of the physical laboratories, obtaining the rank of full professor in 1934. In 1924, Goddard married Esther Christine Kisk, the secretary to the president of Clark. Although the couple had no children, they became devoted to one another and to Goddard's rocket research, in which Esther became very much a partner.

Goddard apparently did not begin serious work on rocket development until early 1909, while a graduate student at Clark. He had, by 1914, obtained a patent for a two-stage powder rocket, followed by patents for a cartridge-loading rocket and a rocket that burned a mixture of gasoline and liquid nitrous oxide. While he was aware of the greater efficiencies of liquid propellants, Goddard found them hard to obtain, preferring instead, smokeless powder, which offered fewer experimental difficulties. Using a steel combustion chamber and a sleeker exhaust nozzle, named for Swedish engineer Carl de Laval, Goddard was able to achieve higher rates of energy efficiency and exhaust velocities than previous rockets had exhibited. He also developed a device that allowed him to fire a rocket in a vacuum, showing that it could operate in the upper atmosphere where air density was small and also demonstrating that it did not require a reaction against the air, as many knowledgeable people at the time supposed.

Until 1916, Goddard had conducted these experiments using the meager funds and facilities provided by Clark, as well as money from his own pocket. No longer able to support the research required to advance his theories, Goddard applied for funding to the Aero Club of America and the Smithsonian Institution. After several inquiries into his request, Goddard reported to the Smithsonian that he had developed a means of propelling meteorological recording devices to heights previously unattainable by sounding balloons, indicating that altitudes of 100–200 mi (161–322 km) could be reached within a year's time. By January 1917, The Smithsonian had awarded Goddard a grant for $5,000. This proved to be the first of many grants from the Smithsonian, Clark University, the Carnegie Institution of Washington, Daniel Guggenheim, and especially the Guggenheim Foundation.

Before the Smithsonian funds could be put to use, America became embroiled in World War I. Supported by the U.S. Army, Goddard and a number of technicians developed both multiple-charge and single-charge recoilless rockets, the latter serving as a prototype for the bazooka which proved effective against tanks during World War II. While tests proved these weapons successful, the armistice intervened before they could be employed. Once World War I was over, Goddard's department head at Clark prodded him into publishing the results of his solid-propellant rocket researches in a paper entitled "A Method of Reaching Extreme Altitudes," which appeared in the *Smithsonian Miscellaneous Collections*. In it, Goddard not only explained the experiments he had conducted, but laid the foundations for much of the early theory of modern rocketry. While devoted primarily to the solid propellants he had used in his research, the paper did mention the greater efficiencies of propellants such as hydrogen and **oxygen** used in their liquid states. The paper briefly discussed the use of stages (propulsion units coupled together to fire in sequence) in order to reach extreme altitudes, and included numerous calculations of such matters as the reduced resistance a rocket would face as it climbed higher and entered less dense portions of the earth's atmosphere.

The reaction to this paper was shaped by a Smithsonian press release emphasizing a point Goddard had not intended as the focus of the work. It suggested the possibility of using a rocket to send a small quantity of flash powder to the dark side of the **Moon**, where, when ignited, it could be viewed from the earth through telescopes, thereby proving that extreme altitude had been reached. The press played up the idea of a moon rocket, and Goddard was embarrassed by the publicity. His inclination against publicizing his work until rockets were actually capable of reaching such altitudes was reinforced. Nevertheless, he persisted in his rocket development in his native Massachusetts for the next decade. Frustrated at the problems he encountered in using solid propellants, he switched to liquid propellants in 1921, though it was not until March 16, 1926—almost ten years after his initial proposal to the Smithsonian—that he launched the world's first liquid-propellant rocket from a hill in Auburn, Massachusetts. Since this was an important event in the history of rocketry, it is noteworthy that the hill, on his Aunt Effie's farm, had an Indian name meaning "a turning point or place." The small rocket only rose 41 ft (12.5 m)—far short of the altitudes he sought to reach—but it represented a significant beginning to the age of rocket flight, comparable, perhaps, to the Wright brothers' contributions to aviation.

From a number of standpoints, including its **weather** and its population density, Massachusetts was hardly an ideal location for launching noisy, fire-belching rockets. So, when Goddard received a generous $50,000 grant from philanthropist Daniel Guggenheim in mid–1930, he took a two-year leave of absence from Clark University and, with his wife and some technical assistants, rented a farmhouse near Roswell, New Mexico, where he proceeded with his rocket development. Loss of funding after 1932 interrupted his research there, but he returned to Roswell in 1934 to resume his testing. In the process, he invented and patented a large number of innovations, including a gyroscopically-controlled guidance system, and a method for cooling the combustion chamber that used a film of propellant streaming along the sides of the chamber. Parachutes were incorporated for recovery of the rocket and a number of instruments were devised for measuring the rocket's performance. Goddard also searched for ways to make a more lightweight, streamlined rocket casing. But he never succeeded in putting all of these components together to create a vehicle capable of reaching anything close to the 100–200 mi (161–322 km) of altitude he had originally expected to achieve. The greatest height one of his rockets reached was estimated at 8,000–9,000 ft (2,440–2,740 m) in March, 1937.

In 1941, he discontinued his attempt to reach extreme altitudes and began work for the armed forces on defense-related rocket research as he had during World War I. In 1942, he moved his crew of assistants to the Naval Engineering Experimental Station in Annapolis, Maryland, where they worked on developing jet-assisted take-off devices for aircraft, pumps, and a variable-thrust rocket motor that became the basis for the one later used on the Bell X–2 rocket plane, the first aircraft in America to use a throttleable engine. This, like the bazooka, was a very important and tangible result of his research. His many patented inventions were also significant. In June 1960, the Army, Air Force, Navy, and National Aeronautics and Space Administration recognized their importance when they granted Mrs. Esther C. Goddard and the Guggenheim Foundation a settlement of $1,000,000 for the right to use many of Goddard's patents.

Despite his technical achievements, however, Goddard's career remained somewhat flawed by his failure to reach the extreme altitudes he sought, and by his secretive nature and consequent failure to communicate most of the details of his research to other scientists and engineers. In 1936, he did publish another paper entitled "Liquid-propellant Rocket Development." Here, Goddard devoted much more attention to liquid propulsion than he had in 1919, and while he did include pictures of some of his rockets and discussed some of their features, the brevity of his treatment (some seventeen pages in his published papers) made the work of limited utility to other scientists and engineers engaged in rocket development. While some of them were inspired by Goddard's example, for the most part they had to develop their own counterparts to his innovations without the benefit of a detailed knowledge of his pioneering inventions.

Despite this failing, Goddard was a remarkable figure in the history of rocket development. Of the many streets, buildings, and awards named in his honor, perhaps the most significant is NASA's Goddard Space Flight Center, dedicated on March 16, 1961—the 35th anniversary of the first flight of a liquid-propellant rocket. On that occasion, Mrs. Goddard accepted a Congressional Gold Medal presented posthumously to him. A little more than nine years later, Clark University named its new library after Goddard. Since 1958, the National Space Club in Washington, DC, has awarded a Goddard Memorial Trophy for achievement in missiles, rocketry, and space flight. Finally, it might be noted that in 1960, Goddard was the ninth recipient of the Langley Gold Medal, awarded only sparingly since 1910 by the Smithsonian Institution for excellence in aviation.

See also Aerodynamics; Satellite; Spacecraft, manned

GOLDSCHMIDT, VICTOR (1888-1947)

Norwegian geochemist

Victor Goldschmidt, helped lay the foundations for the field of crystal **chemistry**. He was a mineralogist, petrologist, and geochemist who devoted the bulk of his research to the study of the composition of the earth. During his many years as a professor and director of a mineralogical institute in Norway, he also investigated solutions to practical geochemical problems at the request of the Norwegian government.

Victor Moritz Goldschmidt was born on January 27, 1888, in Zürich, Switzerland, to Heinrich Jacob Goldschmidt, a distinguished professor of physical chemistry, and Amelie Kohne. His family left Switzerland in 1900 and moved to Norway, where his father took a post as professor of physical chemists at the University of Christiania (now Oslo). Goldschmidt's family obtained Norwegian citizenship in 1905, the same year he entered the university to study chemistry, **geology**, and **mineralogy**. There he studied under the noted geologist and petrologist Waldemar Brogger, becoming a lecturer in mineralogy and crystallography at the university in 1909.

Goldschmidt obtained his Ph.D. in 1911. His doctoral dissertation on contact metamorphic rocks, which was based on **rock** samples from southern Norway, is considered a classic in the field of **geochemistry**. It served as the starting point for an investigation of the **chemical elements** that Goldschmidt pursued for three decades. In 1914, he became a full professor and director of the University of Christiana's mineralogical institute. In 1917, the Norwegian government asked Goldschmidt to conduct an investigation of the country's mineral resources, as it needed alternatives to chemicals that had been imported prior to World War I and were now in short supply. The government appointed him Chair of the Government Commission for Raw Materials and head of the Raw Materials Laboratory.

This led Goldschmidt into a new **area** of research—the study of the proportions of chemical elements in the earth's **crust**. His work was facilitated by the newly developed science of x-ray crystallography, which allowed Goldschmidt and his colleagues to determine the crystal structures of 200 compounds made up of 75 elements. He also developed the first tables of atomic and ionic radii for many of the elements, and showed how the hardness of **crystals** is based on their structures, ionic charges, and the proximity of their atomic particles.

In 1929, Goldschmidt moved to Gottingen, Germany, to assume the position of full professor at the Faculty of Natural Sciences and director of its mineralogical institute. As part of his investigation of the apportionment of elements outside the earth and its atmosphere, he began studying meteorites to ascertain the amounts of elements they contained. He researched numerous substances, including germanium, gallium, scandium, beryllium, selenium, arsenic, chromium, nickel, and zinc, using materials from both the earth and meteorites to devise a model of Earth. In this model, elements were distributed in different parts of Earth based on their charges and sizes. Goldschmidt stayed at Gottingen until 1935, when Nazi anti-Semitism made it impossible for him to continue his work. Returning to Oslo, he resumed work at the university there and assembled data he had collected at Gottingen on the distribution of chemical elements in Earth and in the cosmos. He also began studying ways to use Norwegian **olivine** rock for use in industry.

When World War II began, Goldschmidt had confrontations with the Nazis that resulted in his imprisonment on several occasions. He narrowly escaped internment in a concentration camp in 1943 when, after the Nazis arrested him, he was rescued by the Norwegian underground. They managed to secretly get him onto a boat to Sweden, where fellow scientists arranged for a flight to Scotland.

In Scotland, Goldschmidt worked at the Macaulay Institute for **Soil** Research in Aberdeen. Later during the war, he worked as a consultant to the Rothamsted Agricultural Experiment Station in England. As reported in *Chemists,* Goldschmidt carried with him a cyanide suicide pill for use in the event the Nazis invaded England. When a colleague asked him for one, he responded, "Cyanide is for chemists; you, being a professor of mechanical engineering, will have to use the rope."

After the war, Goldschmidt returned to Oslo and his job as professor and director of the geological museum. There he worked on a newly equipped raw materials laboratory supplied by the Norwegian Department of Commerce. He continued his work until his death on March 20, 1947.

Goldschmidt was a member of the Royal Society and the Geological Society of London, the latter of which awarded him the Wollaston Medal in 1944. He was also an honorary member of the British Mineralogical Society, the Geological Society of Edinburgh, and the Chemical Society of London. He wrote over 200 papers as well as a treatise, *Geochemistry,* which was published posthumously in 1954.

See also Mineralogy

GONDWANALAND • *see* SUPERCONTINENTS

GPS (GLOBAL POSITIONING SYSTEM)

Long before the **space** age, people used the heavens for navigation. Besides relying on the **Sun**, **Moon**, and stars, the early travelers invented the magnetic compass, the sextant, and the seagoing chronometer. Eventually, radio navigation in which a position could be determined by receiving radio signals broadcast from multiple transmitters came into existence. Improved high frequency signals gave greater accuracy of position, but they were blocked by mountains and could not bend over the horizon. This limitation was overcome by moving the transmitters into space on Earth-orbiting satellites, where high frequency signals could accurately cover wide areas.

The principle of **satellite** navigation is relatively simple. When a transmitter moves toward an observer, radio waves have a higher frequency, just like a train's horn sounds higher as it approaches a listener. A transmitter's signal will have a lower frequency when it moves away from an observer. If measurements of the amount of shift in frequency of a satellite radiating a fixed frequency signal with an accurately known orbit are carefully made, the observer can determine a correct position on Earth.

The United States Navy developed such a system, called Transit, in the late 1960s and early 1970s. Transit helped submarines update their on-board inertial navigation systems. After nearly ten years of perfecting the system, the Navy released it for civilian use. It is now used in surveying, fishing, private and commercial maritime activities, offshore oil exploration, and drifting buoys. However, a major drawback to Transit was that it was not accurate enough; a user had to wait until the satellite passed overhead, position fixes required some time to be determined, and an accurate fix was difficult to obtain on a moving platform.

As a result of these shortcomings, the United States military developed another system: Navstar (Navigation Satellite for Time and Ranging) Global Positioning System. This system consists of 24 operational satellites equally divided into six different orbital planes (each containing four satellites) spaced at 60° intervals. The new system can measure to within 33 ft (10 m), whereas Transit was accurate only to 528 ft (161 m).

With the new Global Positioning System (GPS), two types of systems are available with different frequencies and levels of accuracy. The Standard Positioning System (SPS) is used primarily by civilians and commercial agencies. As of midnight, May 1, 2000, the SPS system became 30 times more accurate when President Bill Clinton ordered that the Selective Availability (SA) component of SPS be discontinued. SA was the deliberate decrease of accurate positioning information available for commercial or civilian use. The SPS obtains information from a frequency labeled GPS L1. The United States military has access to GPS L1 and a second frequency, L2. The use of L1 and L2 permits the transfer of data with a higher level of security. In addition to heightened security, the United States military also has access to much more accurate positioning by using the Precise Positioning System (PPS). Use of the PPS is usually limited to the U.S. military and other domestic government agencies.

Both Transit and Navstar use instantaneous satellite position data to help users traveling from one place to another. But another satellite system uses positioning data to report where users have been. This system, called Argos, is a little more complicated: an object on the ground sends a signal to a satellite, which then retransmits the signal to the ground. Argos can locate the object to within 0.5 mi (0.8 km). It is used primarily for environmental studies. Ships and buoys can collect and send data on **weather**, currents, winds, and waves. Land-based stations can send weather information, as well as information about hydrologic, volcanic, and seismic activity. Argos can be used with balloons to study weather and the physical and chemical properties of the atmosphere. In addition, the system is being perfected to track animals.

Use of the GPS system in our everyday lives is becoming more frequent. Equipment providing and utilizing GPS is shrinking both in size and cost, while it increases in reliability. The number of people able to use the systems is also increasing. GPS devices are being installed in cars to provide directional, tracking, and emergency information. People who enjoy the outdoors can pack hand held navigational devices that show their position while exploring uncharted areas. Emergency personnel can respond more quickly to 911 calls thanks to tracking signal devices in their vehicles and in the cell phones of the person making the call. As technology continues to advance the accuracy of navigational satellite and without the impedance of Selective Availability, the uses for GPS will continue to develop.

See also Archeological mapping; Weather satellite

GRANITE

Granite, which makes up 70–80% of Earth's **crust**, is an igneous **rock** formed of interlocking **crystals** of **quartz**, **feldspar**, mica, and other **minerals** in lesser quantities. Large masses of granite are a major ingredient of mountain ranges. Granite is a plutonic rock, meaning that it forms deep underground. Slow cooling gives atoms time to migrate to the surfaces of growing crystals, resulting in a coarse or mottled crystalline structure easily visible to the naked eye.

Geologists have debated rival theories of granite's origin for over 150 years. The two theories most favored today are the magmatic theory and the hypermetamorphic theory. Supporters of the magmatic theory observe that granite is strongly associated with mountain ranges, which in turn tend to follow continental edges where one plate is being subducted (wedged under another). Tens of kilometers beneath the continental edge, the pressure and friction caused by subduction are sufficient to melt large amounts of rock. This melted rock or **magma** ascends toward the surface as large globules or plutons, each containing many cubic kilometers of magma. A **pluton** does not emerge suddenly onto the surface but remains trapped underground, where it cools slowly and may be repeatedly injected from beneath with pulses of fresh magma. To become surface rock, a solidified pluton must finally be uplifted to the surface and stripped bare by **erosion**.

The ultrametamorphic theory, in contrast, argues that granite is not formed from raw magma but consists of sedimentary rock thoroughly melted and re-crystallized. Most geologists now argue that granites can be formed by magmatism, ultrametamorphosis, or a combination of both.

Until recently, geologists thought that plutons of granitic magma would require millions of years to ascend to the surface. However, laboratory experiments with melted rock has shown that granitic magma is thin and runny enough (i.e., of low viscosity) to squirt rapidly upward to the surface through small cracks in the crust. Granite plutons may thus be created in 1,000–100,000 years, rather than in the millions of years previously thought. The precise origin and process of granite formation continues to be a subject of active research.

See also Bowen's reaction series; Convergent plate boundary; Plate tectonics

GRANULITE • *see* METAMORPHIC ROCK

GRAPHITE

Graphite is a soft, black, metallic mineral composed of the element **carbon**. It is nontoxic and rubs off easily on rough surfaces, which is why graphite mixed with fine **clay**, rather than actual **lead**, is used to make pencil leads. The word graphite derives from the Greek *gréphein*, to write or draw.

Graphite has the same chemical formula as **diamond** (C), yet the two **minerals** could hardly be more unlike. Diamond is the hardest of minerals, graphite one of the softest; diamond is transparent, graphite opaque; and diamond is almost twice as dense as graphite. These radically different properties arise from the way the atoms are arranged in each substance. In graphite, carbon atoms are linked in hexagonal sheets resembling chicken-wire fencing. These sheets slide over each other easily, which accounts for graphite's slipperiness. In diamond, carbon atoms are linked in a potentially endless matrix of tetrahedra (four-cornered pyramids), an extremely strong arrangement. Surprisingly, however, graphite is stable under ordinary atmospheric conditions and diamond is not; that is, at standard **temperature** and pressure diamond transforms spontaneously to graphite. The rate of transformation is extremely slow because carbon atoms organized into diamond are separated from the lower-energy graphite state by an activation-energy barrier similar to that which keeps an explosive from going off until triggered by a spark.

The carbon in most graphite and diamonds derives from living things. The organic (carbon-containing) remains of organisms may be transformed into **coal** or into impurities in **limestone**; under some conditions, metamorphosis of these rocks purifies these organic materials to produce graphite. Further metamorphosis under extremely high pressures, such as occur many miles underground, is needed to produce diamond.

Because graphite is resistant to heat and slows neutrons, it was used in the early years of nuclear-power research as a matrix to contain radioactive fuel elements and moderate their chain reaction. Early atomic reactors were termed atomic piles because they consisted mostly of large piles of graphite blocks. Graphite is used not only in pencils, but also as a lubricant for locksmiths and for bearings operating in vacuum or at high temperatures. Because it is both conductive and slippery, graphite is used in generator brushes. It is also employed in making metallurgical crucibles and electrical batteries. Most of the graphite used is manufactured from coal in electrical furnaces, not mined.

See also Chemical bonds and physical properties; Chemical elements

GRAVITATIONAL CONSTANT

The gravitational constant is fundamental quantity of the universe. The gravitational constant, G, was the first great universal constant of **physics** (the others subsequently being the speed of light and Planck's constant) and modern physicists still argue its importance and relationships to **cosmology**. Regardless, almost all the major theoretical frameworks dictate that the value for the gravitational constant (G) is in some regard related to the large-scale structure of the cosmos. Ironically, despite centuries of research, the gravitational constant, G, is—by a substantial margin—the least understood, most difficult to determine, and least precisely known fundamental constant value. The quest for "G" provides a continuing challenge to the experimental ingenuity of physicists, and often spurs new generations of physicists to recapture the inventiveness and delicacy of measurement first embodied in the elegant experiments conducted by English physicist Henry Cavendish (1731–1810).

The Cavendish constant “G” must not be confused with the “g” (designated in lowercase) that geophysicists use to designate gravitational acceleration (i.e., a change in the velocity of an object due to the gravitational field (commonly referred to as the gravitational force) of the earth that is due to the mass of the earth. Although the gravitational field of the earth fluctuates with the mass underneath the **area** in question, the overall average “g” is 9.80665 m/s^2.

In 1798, Cavendish performed an ingenious experiment that led to the determination of the gravitational constant (G). Cavendish used a carefully constructed experiment that utilized a torsion balance to measure the very small gravitational attraction between two masses suspended by a thin fiber support. (Cavendish actually measured the restoring torque of the fiber support). Cavendish’s experimental methodology and device design was not novel. Similar equipment had been designed by English physicist John Mitchell (1724–1793), and a similar apparatus had been designed by French physicist Charles Coulomb and others for electrical measurements and calibrations. Cavendish’s use, however, of the torsional balance to measure the gravitational constant of Earth, was a triumph of empirical skill.

Cavendish balanced his apparatus by placing balls of identical mass at both ends of a crossbar suspended by a thin wire. By **lead** balls of known mass, Cavendish was able to account for both the masses in the Newtonian calculation and thereby allowing a determination of the gravitational constant (G). The Cavendish experiment worked because not much force was required to twist the wire suspending the balance. In addition, Cavendish brought relatively large masses close to the smaller weights—actually on symmetrically opposite sides of the weights—so as to double the actual force and make the small effects more readily observable. Over time, due to the mutual gravitational attraction of the weights the smaller balls moved toward the larger masses. The smaller balls moved because of their smaller mass and inertia (resistance to movement). Cavendish was able to measure the force of the gravitational attraction as a function of the time it took to produce any given amount of twist in the suspending wire. The value of the gravitational constant determined by this method was not precise by modern standards (only a 7% precision but with 1% accuracy) but was an exceptional value for the eighteenth century given the small forces being measured. Because all objects exert a gravitational “pull,” precision in Cavendish type experiments is often hampered by a number of factors, including underlying **geology** or factors as subtle as movements of furniture or objects near the experiment.

The Cavendish experiment was, therefore, a milestone in the advancement of scientific empiricism. In fact, accuracy of the Cavendish determination remained unimproved for almost another century until Charles Vernon Boys (1855–1944) used the Cavendish Balance to make a more accurate determination of the gravitational constant. More importantly, the Cavendish experiment proved that scientists could construct experiments that were able to measure very small forces. Cavendish’s work spurred analysis of the fundamental force of electromagnetism (a fundamental force far stronger than gravity) and gave confidence to the scientific community that Newton’s laws were not only valid, they were also testable on exceedingly small scales.

In modern physics, the speed of light, Planck’s constant, and the gravitational constant are among the most important of fundamental constants. According to **relativity theory**, G is related to the amount of space-time curvature caused by a given mass. Modern concepts of gravity and of the ramifications of the value of the gravitational constant are subject to seemingly constant revision as scientists aim to extend the linkage between the gravitational constant (G) and other fundamental constants. Although profoundly influential and powerful on the cosmic scale, the force of gravity is weak in terms of human dimensions. Accordingly, the masses must be very large before gravitational effects can be easily measured. Even using modern methods, different laboratories often report significantly different values for G.

See also Gravity and the gravitational field

GRAVITY AND THE GRAVITATIONAL FIELD

Geophysicists utilize slight variations in gravitational force to characterize the mass of subsurface features. Particularly useful in **petroleum** exploration, subtle gravitational field differences can help identify solid subsurface plutonic bodies or fluid filled reservoirs.

1n 1687, English physicist **Sir Isaac Newton** (1642–1727) published a law of universal gravitation in his important and influential work *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)*. In its simplest form, Newton’s law of universal gravitation states that bodies with mass attract each other with a force that varies directly as the product of their masses and inversely as the square of the distance between them. This mathematically elegant law, however, offered a remarkably reasoned and profound insight into the mechanics of the natural world because it revealed a cosmos bound together by the mutual gravitational attraction of its constituent particles. Moreover, along with Newton’s laws of motion, the law of universal gravitation became the guiding model for the future development of physical law.

Newton’s law of universal gravitation was derived from German mathematician and astronomer Johannes Kepler’s (1571–1630) laws of planetary motion, the concept of “action-at-a-distance,” and Newton’s own laws of motion. Building on Italian astronomer and physicist Galileo Galilei’s (1564–1642) observations of falling bodies, Newton asserted that gravity is a universal property of all matter. Although the force of gravity can become infinitesimally small at increasing distances between bodies, all bodies of mass exert gravitational force on each other. Newton extrapolated that the force of gravity (later characterized by the gravitational field) extended to infinity and, in so doing, bound the universe together.

Newton's law of gravitation, mathematically expressed as $F= (G)(m_1\ m_2)\ /r^2$, stated that the gravitational attraction between two bodies with masses m_1 and m_2 was directly proportional to the masses of the bodies, and inversely proportional to the square of the distance (r) between the centers of the masses. Accordingly, a doubling of one mass resulted in a doubling of the gravitational attraction while a doubling of the distance between masses resulted in a reduction of the gravitational force to a fourth of its former value. Nearly a century passed, however, before English physicist Henry Cavendish (1731–1810) was to determine the missing **gravitational constant** (G) that allowed a reasonably accurate determination of Earth's actual gravitational force.

The force exerted by a gravitational field on a body, such as forces produced by Earth's gravitational field, is called the weight of the body. The weight of a body is equal to the product of its mass m and the acceleration due to gravity g, (w = mg). Weight should not be confused with mass, which is an intrinsic property of matter that is not altered by an change in the gravitational field (i.e., the mass of an object on Earth is the same in the lower gravity environment on the **Moon**).

Newton's second law states that the net force F acting on an object is equal to the mass of the object m multiplied by its acceleration a (F = ma). Freely falling bodies experience acceleration (g) due to Earth's gravitational field. The force of this field is directed towards the center of Earth. By applying Newton's second law to freely falling bodies, with a = g and F = w, the weight of the body is given as w = mg. Because weight depends upon the gravitational field, it varies with geographical location. Because g decreases with increasing distance from the center of Earth, bodies weigh less at higher altitudes than at sea level. Because of this, weight, unlike mass, is not an inherent property of a body.

The value of "g" ($9.82\ m/s^2$) is the average measure of the strength of Earth's gravitational field (i.e., the acceleration produced on a mass regardless of the composition of the mass.) The value of "g" can vary locally depending on subsurface mass (e.g., plutonic bodies) and so the value ($9.82\ m/s^2$) is an average. Using "g" the gravitational field can then be expressed as force per kilogram exerted by Earth's gravitational field. Although Earth's gravitational field extends to infinity (i.e., as do all other objects with mass in the universe, Earth's gravitational field affects all other entities with mass), because the magnitude of the force of gravity declines as the square of the distance between objects, the force drops dramatically as objects move away from Earth.

Astronauts orbiting Earth do not experience weightlessness because of a lack of gravity. Rather, the apparent weightlessness in a decreased Earth gravity environment results from uniform acceleration toward Earth in such a way that the spacecraft and all objects in it are constantly falling toward Earth in a manner akin to the objects inside a free-falling elevator. In order to achieve orbit, rockets must be powerful enough to achieve escape velocity, the velocity that, at a minimum, allows their vertical "fall" to match the falling away of Earth spherical surface beneath them. Earth's escape velocity measures 6.959 mi/s (11.2 km/s)—more than 25,000 mph.

A tremendous amount of thrust is required to overcome Earth's gravitational field and lift the Space Shuttle into orbit. *U.S. National Aeronautics and Space Administration (NASA).*

Weight is usually expressed in pounds or grams. Although weight and mass are not synonymous terms, they are often used interchangeably. One concept associated with weight is Archimedes' principle that states that a body immersed in a fluid is acted upon by a force equal and opposite in direction to the weight of the displaced fluid. This principle explains the buoyancy of ships, as well as the rise of helium filled balloons.

Another important property associated with weight is specific gravity. The specific gravity of a material is the ratio of the weight of a given volume of that substance to the weight of an equal volume of **water**. For example, because of the salt, the specific gravity of a **saltwater** solution is greater than one. This high specific gravity gives saltwater its large buoyancy power because the weight of the volume displaced by an object in the ocean is larger than the weight of the volume displaced by the same object in **freshwater**.

The molecular weight of a substance is usually expressed in **atomic mass** units which is exactly 1/12 the mass of a carbon-12 **atom**.

Although Newton's law of gravitation offered no fundamental explanatory mechanism for gravity, it's usefulness of explanation lies in a higher level of cause and effect. An explanation of gravity continues to elude physicists. The two great theories of modern physics—relativity theory and quantum theory—explain gravity in very different ways. According to **relativity theory**, gravity is a consequence of the fusion of

space and time. Quantum theory proposes that graviton particles (as of yet undiscovered) act as bosons (carriers) of gravitational force.

See also Aerodynamics; Astronomy; Atomic mass and weight; Aviation physiology; Big Bang theory; Crust; Earth (planet); Gravitational constant; Mohs' scale; Petroleum detection; Quantum theory and mechanics

GREAT BARRIER REEF

The Great Barrier Reef lies off the northeastern coast of **Australia** and is the largest structure ever made by living organisms including human beings, consisting of the skeletons of tiny coral polyps and hydrocorals bounded together by the soft remains of coralline algae and microorganisms.

The Great Barrier Reef is over 1,250 mi (2,000 km) long and is 80,000 mi^2 (207,000 km^2) in surface **area**, which is larger than the island of Great Britain. It snakes along the coast of the continent of Australia, roughly paralleling the coast of the State of Queensland, at distances ranging 10–100 mi (16–160 km) from the shore. The reef is so prominent a feature on Earth that it has been photographed from satellites. The reef is located on the **continental shelf** that forms the perimeter of the Australian landmass where the ocean **water** is warm and clear. At the edge of the continental shelf and the reef, the shelf becomes a range of steep cliffs that plunge to great depths with much colder water. The coral polyps require a **temperature** of at least 70°F (21°C), and the water temperature often reaches 100°F (38°C).

The tiny coral polyps began building their great reef in the **Miocene Epoch** that began 23.7 million years ago and ended 5.3 million years ago. The continental shelf has subsided almost continually since the Miocene Epoch. In response, the reef has grown upward with living additions in the shallow, warm water near the surface; live coral cannot survive below a depth of about 25 fathoms (150 ft, or 46 m) and also depend on the salt content in seawater. As the hydrocorals and polyps died and became cemented together by algae, the spaces between the skeletons were filled in by wave action that forced in other debris called infill to create a relatively solid mass at depth. The upper reaches of the reef are more open and are riddled with grottoes, canyons, caves, holes bored by mollusks, and many other cavities that provide natural homes and breeding grounds for thousands of other species of sea life. The Great Barrier Reef is, in reality, a string of 2,900 reefs, cays, inlets, 900 islands, lagoons, and shoals, some with beaches of **sand** made of pulverized coral.

The reef is the product of over 350 species of coral and red and green algae. The number of coral species in the northern section of the reef exceeds the number (65) of coral species found in the entire Atlantic Ocean. Polyps are the live organisms inside the coral, and most are less than 0.3 in (8 mm) in diameter. They feed at night by extending frond-like fingers to wave zooplankton toward their mouths. In 1981, marine biologists discovered that the coral polyps spawn at the same time on one or two nights in November. Their eggs and sperm form an orange and pink cloud that coats hundreds of square miles of the ocean surface. As the polyps attach to the reef, they secrete lime around themselves to build secure turrets or cups that protect the living organisms. The daisy- or feather-like polyps leave **limestone** skeletons when they die. The creation of a 1 in (2.5 cm) thick layer of coral takes five years.

The coral is a laboratory of the living and once-living; scientists have found that coral grows in bands that can be read much like the rings in trees or the icecaps in polar regions. By drilling cores 25 ft (7.6 m) down into the coral, 1,000 years of lifestyles among the coral can be interpreted from the density, skeleton size, band thickness, and chemical makeup of the formation. The drilling program also proved that the reef has died and revived at least a dozen times during its 25-million-year history, but it should be understood that this resiliency predated human activities. The reef as we know it is about 8,000 years old and rests on its ancestors. In the early 1990s, study of the coral cores has yielded data about temperature ranges, rainfall, and other **climate** changes; in fact, rainfall data for design of a dam were extracted from the wealth of information collected from analysis of the coral formation.

Animal life forms flourish on and along the reef, but plants are rare. The Great Barrier Reef has a distinctive purple fringe that is made of the coralline or encrusting algae *Lithothamnion* (also called stony seaweed), and the green algae *Halimeda discodea* that has a creeping form and excretes lime. The algae are microscopic and give the coral its many colors; this is a symbiotic relationship in which both partners, the coral and the algae, benefit. Scientists have found that variations in water temperature stress the coral causing them to evict the resident algae. The loss of color is called coral bleaching, and it may be indicative of **global warming** or other effects like El Niño.

This biodiversity makes the reef a unique ecosystem. Fish shelter in the reef's intricacies, find their food there, and spawn there. Other marine life experience the same benefits. The coastline is protected from waves and the battering of storms, so life on the shore also thrives.

See also El Niño and La Niña phenomena; Greenhouse gases and greenhouse effect; Tropical cyclone

GREAT CIRCLE • *see* LATITUDE AND LONGITUDE

GREAT LAKES

The Great Lakes are a system of five large **freshwater** lakes in central North America—Lake Erie, Lake Huron, Lake Michigan, Lake Ontario, and Lake Superior—that drain into the Atlantic Ocean via the St. Lawrence Seaway. Combined, the Great Lakes constitute the largest surface **area** of unfrozen fresh **water** in the world: 94,850 mi^2 (245,660 km^2), an area larger than the United Kingdom. Except for Lake Michigan, which is wholly contained in the United States, the Great Lakes form a natural segment of the U.S.-Canadian border.

Lake Superior is the largest of the five lakes by almost 10,000 mi^2 (41,682 km^2), and has the greatest average (and maximum) depth. As a result, Lake Superior contains slightly more water than all the other Great Lakes combined—almost 3,000 mi^3 (12,504 km^3). The deepest parts of all the Great Lakes except Lake Erie are below sea level; in Lake Superior's case, over 600 ft (183 m) below.

Lake Superior has an average depth of 487 ft (148 m), a maximum depth of 1,302 ft (397 m) and covers 31,820 mi^2 (82,413 km^2). Lake Huron has an average depth of 195 ft (59 m), a maximum depth of 750 ft (229 m), and covers 23,010 mi^2 (59,596 km^2). Lake Michigan, covering 22,400 mi^2 (58,016 km^2), has an average depth of 276 ft (84 m), and a maximum depth of 923 ft (281 m). Lake Erie has an average depth of 62 ft (19 m), a maximum depth of 210 ft (64 m), and covers approximately 9,930 mi^2 (25,719 km^2). Lake Ontario, the smallest of the Great Lakes in terms of surface area (7,520 mi^2/19,477 km^2), has an average depth of 62 ft (19 m) but reaches a maximum depth of 778 ft (237 m).

The Great Lakes drain 295,800 mi^2 (766,118 km^2) of watershed (counting the surfaces of lakes themselves), or about 3% of the continent. Half the water entering the lakes evaporates; the rest flows from lake to lake, west to east, until it reaches Lake Ontario and then the St. Lawrence River.

By geological standards, the Great Lakes formed very recently. Prior to the beginning of the **ice ages** of the Pleistocene Epoch—about 1 million years ago—river valleys drained through the areas now occupied by the five lakes. As the ice-sheets flowed southward they favored these preexisting channels, scouring them and so increasing their depth. The latest glacial episode was the Wisconsin **Glaciation**, which ended about 18,000 years ago. When **melting** removed the glacier's enormous weight, the land began to rise. (It is still rising, at about .12 in / 3 mm per year.) This rising of the land, along with deposition of glacial sediments (**moraines**), blocked all drainage from the Great Lakes area except eastward via the St. Lawrence. Lake Superior is the only Great Lake not formed by glacial scouring and deposition of moraines. Lake Superior's basin, although somewhat enlarged by glacial scouring, is the trough of a V-shaped fold in the **rock** termed a **syncline**.

But the Wisconsin glaciation did not simply advance to a most southerly limit, then retreat in an orderly way. It advanced and retreated several times over thousands of years in a three-steps-northward, two-steps-southward fashion. These oscillations partially uncovered and recovered the Great Lakes basins, forming a series of lakes corresponding partly to the modern ones. At one point, a superlake submerged what are today the basins of Superior, Michigan, and Huron. The history of these fluctuations can be traced primarily by the many abandoned beaches that are today found far above water level (often hundreds of feet above). Each abandoned beach records a lake stage or period during which the water level was stable long enough to form a beach. From these and other data, it is known that Erie reached its present level about 10,000 years ago; Ontario about 7,000 years ago; and Superior, Michigan, and Huron only about 3,000 years ago.

Human activity has significantly altered the **chemistry** and ecology of the lower four lakes, which are ringed by such cities as Buffalo, Chicago, Cleveland, Detroit, Gary, Milwaukee, Rochester, Toledo, and Toronto. Sewage and industrial effluents have burdened these lakes increasingly for over a century. (Chicago and several other cities, however, now divert their sewage southward, away from the lakes.) Lake Superior has been less affected by pollution, having no major settlements on its shores.

Another detrimental side-effect of human activity is the introduction into the lake ecosystem, both deliberate and accidental, of non-native species. The sea lamprey (1930s), alewife (probably 1940s), and zebra mussel (1980s) have been particularly destructive to the native lake fauna. Alewives are now the most abundant fish species in the lakes. They suffer intermittent mass die-offs, wash up on the beaches by the millions, and must be removed using bulldozers and trucked away.

See also Drainage basins and drainage patterns; Glacial landforms; Syncline and anticline; Water pollution and biological purification

GREENHOUSE GASES AND GREENHOUSE EFFECT

The greenhouse effect is the physical mechanism by which the atmosphere helps to maintain Earth's surface **temperature** within a range comfortable for organisms and ecological processes. The greenhouse effect is largely a natural phenomenon, but its intensity may be changing because of increasing concentrations of **carbon dioxide** and some other gases in the atmosphere. These increased concentrations are occurring as a result of human activities, especially the burning of fossil **fuels** and the clearing of **forests**. A probable consequence of an intensification of Earth's greenhouse effect will be a significant warming of the atmosphere. This could likely result in important secondary changes, such as a rise in sea level, variations in the patterns of **precipitation**, and large and difficult ecological and socio-economic adjustments.

Earth's greenhouse effect is a well-understood physical phenomenon. Scientists believe that in the absence of the greenhouse effect, Earth's surface temperature would average about –0.4°F (–18°C), which is colder than the **freezing** point of **water**, and more frigid than life could tolerate long term. By slowing the rate at which the planet cools itself, the greenhouse effect helps to maintain Earth's surface at an average temperature of about 59°F (15°C). This is about 59.5°F (33°C) warmer than it would otherwise be, and is within the range of temperature that life can tolerate.

An energy budget is a physical analysis of all of the energy coming into a system, all the energy going out, and any difference that might be internally transformed or stored. Almost all of the energy coming to Earth from outer **space** has been radiated by the closest star, the **Sun**. The Sun emits electromagnetic energy at a rate and spectral quality determined by its surface temperature—all bodies do this, as long as they have a temperature greater than absolute zero, or –459°F

(–273°C). Fusion reactions occurring within the Sun maintain an extremely hot surface temperature, about 10,800°F (6,000°C). As a direct consequence of this surface temperature, about one-half of the Sun's emitted energy is so-called "visible" radiation with wavelengths between 0.4 and 0.7 µm (this is called visible radiation because it is the range of electromagnetic energy that the human eye can perceive), and about one-half is in the near-infrared wavelength range between about 0.7 and 2.0 µm. The Sun also emits radiation in other parts of the **electromagnetic spectrum**, such as ultraviolet and cosmic radiation. However, these are relatively insignificant amounts of energy (although even small doses can cause biological damage).

At the average distance of Earth from the Sun, the rate of input of **solar energy** is about 2 cal cm^{-2} min^{-1}, a value referred to as the solar constant. There is a nearly perfect energetic balance between this quantity of electromagnetic energy incoming to Earth, and the amount that is eventually dissipated back to outer space. The myriad ways in which the incoming energy is dispersed, transformed, and stored make up Earth's energy budget.

On average, one-third of incident solar radiation is reflected back to space by the earth's atmosphere or its surface. The planet's reflectivity (or albedo) is strongly dependent on cloud cover, the density of tiny particulates in the atmosphere, and the nature of the surface, especially the cover of vegetation and water, including **ice** and snow.

Another one-third of the incoming radiation is absorbed by certain gases and vapors in Earth's atmosphere, especially water vapor and **carbon** dioxide. Upon absorption, the solar electromagnetic energy is transformed into thermal kinetic energy (that is, heat, or energy of molecular vibration). The warmed atmosphere then re-radiates energy in all directions as longer-wavelength (7–14 µm) infrared radiation. Much of this re-radiated energy escapes to outer space.

The remaining one-third of the incoming energy from the Sun is transformed or dissipated by the following processes:

Absorption and radiation at the surface

Much of the solar radiation that penetrates to Earth's surface is absorbed by living and non-living materials. This results in a transformation to thermal energy, which increases the temperature of the absorbing surfaces. Over the medium term (days) and longer term (years) there is little net storage of energy as heat. This occurs because almost all of the thermal energy is re-radiated by the surface, as electromagnetic radiation of a longer wavelength than that of the original, incident radiation. The wavelength spectrum of typical, re-radiated electromagnetic energy from Earth's surface peaks at about 10 µm, which is within the long-wave infrared range.

Evaporation and melting of water

Some of the electromagnetic energy that penetrates to Earth's surface is absorbed and transformed to heat. Much of this thermal energy subsequently causes water to evaporate from plant and inorganic surfaces, or it causes ice and snow to melt.

Winds, waves, and currents

A small amount (less than 1%) of the absorbed solar radiation causes mass-transport processes to occur in the **oceans** and lower atmosphere, which disperses of some of Earth's unevenly distributed thermal energy. The most important of these physical processes are winds and storms, water currents, and waves on the surface of the oceans and **lakes**.

Photosynthesis

Although small, an ecologically critical quantity of solar energy, averaging less than 1% of the total, is absorbed by plant pigments, especially chlorophyll. This absorbed energy is used to drive photosynthesis, the energetic result of which is a temporary storage of energy in the inter-atomic bonds of biochemical compounds.

If the atmosphere was transparent to the long-wave infrared energy that is re-radiated by Earth's atmosphere and surface, then that energy would travel unobstructed to outer space. However, so-called radiatively active gases (or RAGs; also known as "greenhouse gases") in the atmosphere are efficient absorbers within this range of infrared wavelengths, and these substances thereby slow the radiative cooling of the planet. When these atmospheric gases absorb infrared radiation, they develop a larger content of thermal energy, which is then dissipated by a re-radiation (again, of a longer wavelength than the electromagnetic energy that was absorbed). Some of the secondarily re-radiated energy is directed back to Earth's surface, so the net effect of the RAGs is to slow the rate of cooling of the planet.

This process has been called the "greenhouse effect" because its mechanism is analogous to that by which a glass-enclosed space is heated by solar energy. That is, a greenhouse's **glass** and humid atmosphere are transparent to incoming solar radiation, but absorb much of the re-radiated, long-wave infrared energy, slowing down the rate of cooling of the structure.

Water vapor (H_2O) and carbon dioxide (CO_2) are the most important radiatively active constituents of Earth's atmosphere. Methane (CH_4), nitrous oxide (N_2O), **ozone** (O_3), and chlorofluorocarbons (CFCs) play a more minor role. On a per-molecule basis, these gases differ in their ability to absorb infrared wavelengths. Compared with carbon dioxide, a molecule of methane is 11–25 times more effective at absorbing infrared, nitrous oxide is 200–270 times, ozone 2,000 times, and CFCs 3,000–15,000 times.

Other than water vapor, the atmospheric concentrations of all of these gases have increased in the past century because of emissions associated with human activities. Prior to 1850, the concentration of CO_2 in the atmosphere was about 280 ppm, while in 1994 it was 355 ppm. During the same period CH_4 increased from 0.7 ppm to 1.7 ppm, N_2O from 0.285 ppm to 0.304 ppm; and CFCs from zero to 0.7 ppb. These increased concentrations are believed to contribute to a hypothesized increase in the intensity of Earth's greenhouse effect, an increase attributable to human activities. Overall, CO_2 is estimated to account for about 60% of this enhancement of the greenhouse effect, CH_4 15%, N_2O 5%, O_3 8%, and CFCs 12%.

The physical mechanism of the greenhouse effect is conceptually simple, and this phenomenon is acknowledged by scientists as helping to keep Earth's temperature within the comfort zone for organisms. It is also known that the concentrations of CO_2 and other RAGs have increased in Earth's atmosphere, and will continue to do so. However, it has proven difficult to demonstrate that a warming of Earth's surface or lower atmosphere has been caused by a stronger greenhouse effect.

Since the beginning of instrumental recordings of surface temperature around 1880, it appears that almost all of the warmest years have occurred during the late 1980s and 1990s. Typically, these warm years have averaged about 1.5–2.0°F (0.8–1.0°C) warmer than occurred during the decade of the 1880s. Overall, Earth's surface air temperature has increased by about 0.9°F (0.5°C) since 1850.

However, the temperature data on which these apparent changes are based suffer from some important deficiencies, including: (1) air temperature is variable in time and space, making it difficult to determine statistically significant, longer-term trends; (2) older data are generally less accurate than modern records; (3) many **weather** stations are in urban areas, and are influenced by "heat island" effects; and (4) **climate** can change for reasons other than a greenhouse response to increased concentrations of CO_2 and other RAGs, including albedo-related influences of volcanic emissions of sulfur dioxide, sulfate, and fine particulates into the upper atmosphere. Moreover, it is well known that the interval 1350 to 1850, known as the Little Ice Age, was relatively cool, and that global climate has been generally warming since that time period.

Some studies have provided evidence for linkages between historical variations of atmospheric CO_2 and surface temperature. Important evidence comes from a core of Antarctic glacial ice that represents a 160,000-year time period. Concentrations of CO_2 in the ice were determined by analysis of air bubbles in layers of known age, while changes in air temperature were inferred from ratios of **oxygen** isotopes (because isotopes differ in weight, their rates of diffusion are affected by temperature in predictably different ways, and this affects their relative concentrations in the glacial ice). Because changes in CO_2 and surface temperature were positively correlated, a potential greenhouse mechanism is suggested. However, this study could not determine whether increased CO_2 might have resulted in warming through an intensified greenhouse effect, or whether warming could have increased CO_2 release from ecosystems by increasing the rate of decomposition of biomass, especially in cold regions.

Because of the difficulties in measurement and interpretation of climatic change using real-world data, computer models have been used to predict potential climatic changes caused by increases in atmospheric RAGs. The most sophisticated simulations are the so-called "three-dimensional general circulation models" (GCMs), which are run on supercomputers. GCM models simulate the extremely complex, mass-transport processes involved in **atmospheric circulation**, and the interaction of these with variables that contribute to climate. To perform a simulation experiment with a GCM model, components are adjusted to reflect the probable physical influence of increased concentrations of CO_2 and other RAGs.

Many simulation experiments have been performed, using a variety of GCM models. Of course, the results vary according to the specifics of the experiment. However, a central tendency of experiments using a common CO_2 scenario (a doubling of CO_2 from its recent concentration of 360 ppm) is for an increase in average surface temperature of 1.8–7.2°F (1–4°C). This warming is predicted to be especially great in polar regions, where temperature increases could be two or three times greater than in the tropics.

One of the best-known models was designed and used by the International Panel on Climate Change (IPCC). This GCM model made assumptions about population and economic growth, resource availability, and management options that resulted in increases or decreases of RAGs in the atmosphere. Scenarios were developed for emissions of CO_2, other RAGs, and sulfate aerosols, which may cool the atmosphere by increasing its albedo and by affecting cloud formation. For a simple doubling of atmospheric CO_2, the IPCC estimate was for a 4.5°F (2.5°C) increase in average surface temperature. The estimates of more advanced IPCC scenarios (with adjustments for other RAGs and sulfate) were similar, and predicted a 2.7–5.4°F (1.5–3°C) increase in temperature by the year 2100, compared with 1990.

It is likely that the direct effects of climate change caused by an intensification of the greenhouse effect would be substantially restricted to plants. The temperature changes might cause large changes in the quantities, distribution, or timing of precipitation, and this would have a large effect on vegetation. There is, however, even more uncertainty about the potential changes in rainfall patterns than of temperature, and effects on **soil** moisture and vegetation are also uncertain. Still, it is reasonable to predict that any large changes in patterns of precipitation would result in fundamental reorganizations of vegetation on the terrestrial landscape.

Studies of changes in vegetation during the warming climate that followed the most recent, Pleistocene, **glaciation**, suggest that plant species responded in unique, individualistic ways. This results from the differing tolerances of species to changes in climate and other aspects of the environment, and their different abilities to colonize newly available habitat. In any event, the species composition of plant communities was different then from what occurs at the present time. Of course, the vegetation was, and is, dynamic, because plant species have not completed their post-glacial movements into suitable habitats.

In any region where the climate becomes drier (for example, because of decreased precipitation), a result could be a decreased **area** of forest, and an expansion of savanna or **prairie**. A landscape change of this character is believed to have occurred in the New World tropics during the Pleistocene glaciations. Because of the relatively dry climate at that time, presently continuous rainforest may have been constricted into relatively small refugia (that is, isolated patches). These forest remnants may have existed within a landscape matrix of savanna and grassland. Such an enormous restructuring of the character of the tropical landscape must have had a tremendous effect on the multitude of rare species that live in that region. Likewise, climate change potentially associated with an intensification of the greenhouse effect would have a devastating effect on Earth's natural ecosystems and the species that they sustain.

There would also be important changes in the ability of the land to support crop plants. This would be particularly true of lands cultivated in regions that are marginal in terms of rainfall, and are vulnerable to **drought** and desertification. For example, important crops such as wheat are grown in regions of the western interior of **North America** that formerly supported natural shortgrass prairie. It has been estimated that about 40% of this semiarid region, measuring 988 million acres (400 million ha), has already been desertified by agricultural activities, and crop-limiting droughts occur there sporadically. This climatic handicap can be partially managed by irrigation. However, there is a shortage of water for irrigation, and this practice can cause its own environmental problems, such as salinization. Clearly, in many areas substantial changes in climate would place the present agricultural systems at great risk.

Patterns of wildfire would also be influenced by changes in precipitation regimes. Based on the predictions of climate models, it has been suggested that there could be a 50% increase in the area of forest annually burned in Canada, presently about 2.5–4.9 million acres (1–2 million ha) in typical years.

Some shallow marine ecosystems might be affected by increases in seawater temperature. Corals are vulnerable to large increases in water temperature, which may deprive them of their symbiotic algae (called zooxanthellae), sometimes resulting in death of the colony. Widespread coral "bleachings" were apparently caused by warm water associated with an **El Niño** event in 1982–83.

Another probable effect of warming could be an increase in sea level. This would be caused by the combination of (1) a thermal expansion of the volume of warmed seawater, and (2) **melting** of polar **glaciers**. The IPCC models predicted that sea level in 2100 could be 10.5–21 in (27–50 cm) higher than today. Depending on the rate of change in sea level, there could be substantial problems for low-lying, coastal agricultural areas and cities.

Most GCM models predict that high latitudes will experience the greatest intensity of climatic warming. Ecologists have suggested that the warming of northern ecosystems could induce a positive feedback to climate change. This could be caused by a change of great expanses of boreal forest and arctic tundra from sinks for atmospheric CO_2, into sources of that greenhouse gas. In this scenario, the climate warming caused by increases in RAGs would increase the depth of annual thawing of frozen soils, exposing large quantities of carbon-rich organic materials in the **permafrost** to microbial decomposition, and thereby increasing the emission of CO_2 to the atmosphere.

It is likely that an intensification of Earth's greenhouse effect would have large climatic and ecological consequences.

Under the auspices of the United Nations Environment Program, various international negotiations have been undertaken to try to get nations to agree to decisive actions to reduce their emissions of RAGs. One recent major agreement came out of a large meeting held in Kyoto, Japan, in 1997. There, industrial countries, such as those of North America and Western **Europe**, agreed to reduce their CO_2 by as much as 5–7% of their 1990 levels by the year 2012. These reductions will be a huge challenge for those countries to achieve.

One possible complementary way to balance the emissions of RAGs would be to remove some atmospheric CO_2 by increasing its fixation by growing plants, especially through the planting of forests onto agricultural land. Similarly, the prevention of deforestation will avoid large amounts of CO_2 emissions through the conversion of high-carbon forests into low-carbon agro-ecosystems.

See also Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Desert and desertification; Earth (planet); El Niño and La Niña phenomena; Forests and deforestation; Fuels and fuel chemistry; Global warming; Ozone layer and hole dynamics; Ozone layer depletion; Petroleum, economic uses of

GREENSTONE BELT

Greenstone belts are generally elongate, **Archean** to Proterozoic terrains comprising intrusive and extrusive **mafic** to ultramafic **igneous rocks**, **felsic** volcanics, and inter-flow or cover **sedimentary rocks**. Greenstone belts occur sandwiched between regions dominated by granitoids and **gneiss**. Greenstones are generally of low to moderate metamorphic grade. The term greenstone comes from the green color of many mafic to ultramafic constituents due to an abundance of chlorite. A common igneous **rock** in greenstones is komatiite. Komatiites are rocks with greater than 18 weight percent magnesium oxide and a well-developed spinifex texture of interlocking bladed or acicular (pointed) **crystals** of **olivine** or pyroxene. Spinifex texture (named after similarities in crystal shape and pattern to the pointed spinifex grass that grows in South **Africa** and Western **Australia**) implies rapid cooling or decompression of the **magma**. Komatiites formed as volcanic flows and less commonly as intrusive sills. Sedimentary sequences within greenstone belts comprise both clastic (e.g., conglomerate, **quartz** arenite, shale and graywacke) and chemically precipitated (e.g., banded **iron** formation and **chert**) components. Greenstones may also be intruded by syn- to post-tectonic granitoids. Greenstone belts check host many major mineral deposits, such as gold and nickel. Greenstone belts were previously often thought to continue to large depths in the **crust**. Reflection seismic profiles over the Norseman Wiluna Belt of the Yilgarn **Craton**, Western Australia, however, indicate that this greenstone belt has a relatively shallow (3.7–5.6 mi [6–9 km]) flat-base and overlies a uniformly thick crust.

Contrasting models have been proposed for the origins of greenstone belts. Some geologists believe magmatic and tectonic processes during formation of greenstone belts in Archaean times were different to present-day **plate tectonics**. Earth's mantle would have then been far hotter. They cite differences between greenstone belts and Phanerozoic orogens (such as the abundance of komatiitic lavas) and point out that there are no modern analogues to greenstone belts. Opponents to Archean plate tectonics contend that greenstone belts commonly represent a laterally continuous **volcano** sedimentary sequence (sometimes on a granite-gneiss basement) essentially undeformed prior to late tectonism and may not therefore represent relics of volcanic chains. They consider that Archaean tectonics was dominated by **mantle plumes** and was possibly analogous to the tectonics of Venus. Greenstone belts are interpreted as oceanic plateaus generated by mantle plumes, similar to plume-generated oceanic plateaus in the southern Caribbean. A mantle plume origin is also proposed for neighboring tonalite-trondhjemite-granodiorite sequences.

The alternate view is that tectonic processes comparable to present-day plate tectonics were operative during the Late Archaean, and possibly were similar to plate tectonics since the Hadean-Archean transition (between 4.0 and 4.2 billion years ago). In a plate tectonic context, greenstones may have formed in volcanic arcs or inter-arc or back-arc basins. Greenstone belts are interpreted to represent collages of oceanic crust, **island arcs**, accretionary prisms, and possible plateaus. Recent experimental work on the origin of komatiitic magmas indicates that they were hydrous and that temperatures for their formation do not indicate that the Archean upper mantle was significantly hotter than today. Komatiites and similar rocks have also been found in younger orogens. Komatiites may not therefore require different tectonic processes or conditions for their formation, as previously thought.

In many granitoid-greenstone terrains, greenstone belts constitute synformal keels between circular to elliptical granitoid bodies. This outcrop pattern is generally thought to be due to deformation resulting solely from the greater density of greenstones compared to underlying granitoid and gneiss. Due to gravitational instability, the underlying, less dense granitoid-gneiss basement domed upwards and rose to form mushroom-shaped bodies called diapirs whilst the denser greenstones sank into the basement. **Shear zones** were formed along some granite-greenstone contacts due to differential vertical displacement and upright **folds** developed in the greenstones. This process of either solid-state and/or magmatic diapirism was independent to any tectonic processes that may have acted on margins to granite-greenstone terrains. The formation of granitoid domes in granite-greenstone terrains has also been attributed to crustal extension (producing metamorphic core complexes) or polyphase folding during regional shortening. The more linear form of some greenstone belts is due to subsequent deformation, especially the **superposition** of regional-scale transcurrent shear zones on early-formed structures.

See also Geologic time

GROUND FOG • *see* FOG

GROUND MORAINE • *see* MORAINES

GROUNDWATER

Groundwater occupies the void **space** in geological strata. It is one element in the continuous process of moisture circulation on Earth, termed the **hydrologic cycle**.

Almost all groundwater originates as surface **water**. Some portion of rain hitting the earth runs off into streams and **lakes**, and another portion soaks into the **soil**, where it is available for use by plants and subject to **evaporation** back into the atmosphere. The third portion soaks below the root zone and continues moving downward until it enters the groundwater. **Precipitation** is the major source of groundwater. Other sources include the movement of water from lakes or streams and contributions from such activities as excess irrigation and seepage from canals. Water has also been purposely applied to increase the available supply of groundwater. Water-bearing formations called aquifers act as reservoirs for storage and conduits for transmission back to the surface.

The occurrence of groundwater is usually discussed by distinguishing between a zone of saturation and a zone of aeration. In the zone of saturation, the pores are entirely filled with water, while the zone of aeration has pores that are at least partially filled by air. Suspended water does occur in this zone. This water is called vadose, and the zone of aeration is also known as the vadose zone. In the zone of aeration, water moves downward due to **gravity**, but in the zone of saturation it moves in a direction determined by the relative heights of water at different locations.

Water that occurs in the zone of saturation is termed groundwater. This zone can be thought of as a natural storage **area** or reservoir whose capacity is the total volume of the pores of openings in rocks.

An important exception to the distinction between these zones is the presence of ancient seawater in some sedimentary formations. The pore spaces of materials that have accumulated on an ocean floor, which has then been raised through later geological processes, can sometimes contain salt water. This is called connate water.

Formations or strata within the **saturated zone** from which water can be obtained are called aquifers. Aquifers must yield water through wells or **springs** at a rate that can serve as a practical source of water supply. To be considered an **aquifer** the geological formation must contain pores or open spaces filled with water, and the openings must be large enough to permit water to move through them at a measurable rate. Both the size of pores and the total pore volume depends on the type of material. Individual pores in fine-grained materials such as **clay**, for example, can be extremely small, but the total volume is large. Conversely, in coarse material such as **sand**, individual pores may be quite large but total volume is less. The rate of movement for fine-grained materials, such as clay, will be slow due to the small pore size, and it may not yield sufficient water to wells to be considered an aquifer. However, the sand is considered an aquifer, even though they yield a smaller volume of water, because they will yield water to a well.

The **water table** is not stationary, but moves up or down depending on surface conditions such as excess precipitation, **drought**, or heavy use. Formations where the top of the saturated zone or water table define the upper limit of the aquifer are called unconfined aquifers. The hydraulic pressure at any level with an aquifer is equal to the depth from the water table, and there is a type known as a water-table aquifer, where a well drilled produces a static water level which stands at the same level as the water table.

A local zone of saturation occurring in an aerated zone separated from the main water table is called a perched water table. These most often occur when there is an impervious strata or significant particle-size change in the zone of aeration, which causes the water to accumulate. A confined aquifer is found between impermeable layers. Because of the confining upper layer, the water in the aquifer exists within the pores at pressures greater than the atmosphere. This is termed an **artesian** condition and gives rise to an artesian well.

Groundwater can be pumped from any aquifer that can be reached by modern well-drilling apparatus. Once a well is constructed, hydraulic pumps pull the water up to the surface through pipes. As water from the aquifer is pulled up to the surface, water moves through the aquifer towards the well. Because water is usually pumped out of an aquifer more quickly than new water can flow to replace what has been withdrawn, the level of the aquifer surrounding the well drops, and a cone of depression is formed in the immediate area around the well.

Groundwater can be polluted by the spilling or dumping of contaminants. As surface water percolates downward, contaminants can be carried into the aquifer. The most prevalent sources of contamination are **waste disposal**, the storage, transportation and handling of commercial materials, mining operations, and nonpoint sources such as agricultural activities. Two other forms of groundwater pollution are the result of pumping too much water too quickly, so that the rate of water withdrawal from the aquifer exceeds the rate of aquifer recharge. In coastal areas, salty water may migrate towards the well, replacing the fresh water that has been withdrawn. This is called salt-water intrusion. Eventually, the well will begin pulling this salt water to the surface; once this happens, the well will have to be abandoned. A similar phenomenon, called connate ascension, occurs when a **freshwater** aquifer overlies a layer of **sedimentary rocks** containing connate water. In some cases, over pumping will cause the connate water to migrate out of the sedimentary rocks and into the freshwater aquifer. This results in a brackish, briney contamination similar to the effects of a salt-water intrusion. Unlike salt water intrusion, however, connate ascension is not particularly associated with coastal areas.

Groundwater has always been an important resource, and it will become more so in the future as the need for good quality water increases due to urbanization and agricultural production. It has recently been estimated that 50% of the drinking water in the United States comes from groundwater; 75% of the nation's cities obtain all or part of their supplies from groundwater, and rural areas are 95% dependent upon it. For these reasons every precaution should be taken to protect groundwater purity. Once contaminated, groundwater is difficult, expensive, and sometimes impossible to clean up.

See also Freshwater; Hydrogeology

GUERICKE, OTTO VON (1602-1686)

German politician and physicist

Otto von Guericke, born in Magdeburg, Germany, was a scientific showman during the seventeenth century. He studied mathematics, law, and engineering. Following travels to England and France, Guericke returned to Magdeburg in 1627 and became a politician. Unfortunately, this was during the Thirty Years' War; Guericke and his family had to flee the city in 1631. Following the war, he returned and helped rebuild the city, becoming mayor in 1646. Twenty years later he became a noble and added "von" to his name.

Otto von Guericke spent his leisure time dabbling in science, and he became involved in discussions surrounding the possibility of the existence of a vacuum. Most scientists were inclined to disavow that a vacuum could exist, primarily because of the teachings of Aristotle. Aristotle's theory was a masterpiece of reverse logic; he believed that if the air became less dense, an object would be able to move faster. If there was a vacuum, he erroneously added, an object could move with infinite speed, but because infinite speed was not possible, a vacuum was not possible either.

Unlike scientists who blindly accepted the ancient teachings, Guericke attempted to get a definite answer by experimentation. In 1650, he built the first air pump and proceeded to put on his production.

Guericke's first vacuum experiment was with a bell. Placing it in a vessel from which he had removed the air, thereby creating a vacuum, he showed that the bell could not be heard. This proved one of Aristotle's theories, which stated that sound would not travel through a vacuum. In addition, Guericke showed that lit candles would go out, and animals could not live in a vacuum.

For added drama, Guericke tied a rope to a piston in a cylinder and had fifty men pulling on it as he created a vacuum on the other side of the piston. The piston was drawn down into the cylinder in spite of the men trying to pull it the other direction.

For his next trick, in 1657, Guericke fitted two 12–ft (3.6–m) diameter metal hemispheres together, removed the air and created a vacuum that held the halves in place. Sixteen horses were unable to pull the hemispheres apart, yet when air was returned to the sphere, the halves fell apart. Emperor Ferdinand III, in the audience, was impressed. Guericke had placed the air valve in the bottom of his sphere because he was under the impression that air, like **water**, would seek the lowest level. He discovered that air could be removed no matter where the valve was located. Obviously the air was evenly distributed throughout the sphere. This led him to speculate that air decreased in density as one's altitude above the earth increased. He used this knowledge to build a water barometer in 1672, and used it to forecast the **weather**.

In addition to his experiments with the vacuum, Guericke built a device that created static **electricity**, similar to

Robert Van de Graaff's (1901–1967) generator. A sphere of sulfur was rotated on a shaft. When it was rubbed, it built up a static charge that caused sizeable electric sparks to discharge. Guericke did not realize the electrical effect was a special phenomenon, but he was responsible for instigating a century of investigation by others.

Guericke also was interested in **astronomy**, suggesting that **comets** were members of the **solar system** and made regular returns as they orbited around the **sun**. **Edmond Halley** jumped on this idea and became famous when his observed comet returned precisely when he predicted. Guericke also believed that a magnetic force caused celestial objects to interact with each other across empty **space**. Isaac Newton would show that interaction did occur, but not because of **magnetism**.

After holding the position of mayor of Magdeburg for 35 years, Guericke retired. He died in Hamburg, Germany at the age of 83.

See also Atmospheric pressure; Electricity and magnetism; Gravity and the gravitational field

GULF OF MEXICO

The Gulf of Mexico is a unique, semi-enclosed sea located between the Yucatan and Florida peninsulas, at the southeast shores of the United States. The Gulf of Mexico borders five of the 50 United States (Alabama, Florida, Louisiana, Mississippi, and Texas), and also Cuba and the eastern part of Mexico. Sometimes it is also called America's Sea. The Straits of Florida divides the Gulf from the Atlantic Ocean, while the Yucatan Channel separates it from the Caribbean Sea. The Gulf of Mexico covers more than 600,000 mi^2 (almost 1.5 million km^2), and in some areas its depth reaches 12,000 ft (3660 m), where it is called Sigsbee Deep, or the "Grand **Canyon** under the sea." About two-thirds of the contiguous United States (31 states between the Rocky Mountains and the Appalachian Mountains) belongs to the watershed **area** of the Gulf of Mexico, while it receives **freshwater** from 33 major river systems, and many small **rivers**, creeks, and streams. This watershed area covers a little less than two million mi^2 (almost 5 million km^2).

The currents in the Gulf of Mexico form a complex system. Its dominant feature is the Caribbean Current, coming from the warm Caribbean Sea by the Yucatan Channel, meandering around in the Gulf, then leaving through the Straits of Florida. Together with the Antilles Current, the Caribbean Current forms the **Gulf Stream**. The Gulf of Mexico has **tides** (the ocean waters' response to the Moon's and Sun's gravitational pull) of normally 2 ft (0.6 m) or less.

According to the modified Trewartha climate system, most of the Gulf Coast area is in the subtropical climate region with a summer **precipitation** maximum. The southern tip of the Yucatan Peninsula belongs to the savanna climate, and between the subtropical and the savanna lies a small area of tropical dry savanna. The hurricane season is between June and November, when hurricanes from the Atlantic Ocean, the Caribbean Sea, or the Gulf of Mexico can damage the Gulf shore, and beyond it. These hurricanes also help to balance the salinity of the **water**, while also moderating the atmosphere. The Gulf of Mexico plays an important role as a fuel injector for hurricanes before landfall, since major hurricanes are rapidly intensified by passing over deep and warm water.

The Gulf of Mexico has several environmental quality problems originating either from natural processes, or from anthropogenic pollution, or their combination. The problems range from **erosion**, and topsoil washing from the land into the Gulf, to oil spills and hazardous material spills, or trash washing ashore. These problems not only affect the estuaries, wetlands, and water quality in the Gulf, but have led to problems such as hypoxia (a zone of oxygen-depleted water), declining fish catch, contaminated fish, fish kills, endangered species, and air and water quality problems.

The role of the Gulf of Mexico is complex. The Gulf hosts important ocean currents (the area where hurricanes can gain strength before hitting land). The Gulf of Mexico and the Caribbean area contain some of the most spectacular wildlife in the world. The Gulf also partially supplies moisture for the North American Monsoon, and is also an important area for recreation and commercial fisheries. Many onshore refineries and offshore drilling platforms operate in the Gulf area, and produce about a quarter of the crude oil and almost one third of the **natural gas** in the United States. The Gulf also links the ports of the five southern states and Mexico with the ocean; about half of all the cargo shipped in and out of the United States travels through the Gulf. The Gulf of Mexico provides food, energy, jobs, recreation, and government revenue, not only benefiting the population on the shoreline of the Gulf, but the whole country.

See also Delta; Dunes; Estuary; Gulf stream; Petroleum extraction; Red tide; Rip current; Seawalls and beach erosion

GULF STREAM

The Gulf Stream is a well-known, fast, intense, and warm ocean current in the North Atlantic Ocean. Its path goes from the **Gulf of Mexico** and the Caribbean Sea, along the eastern coast of the United States, heading to the northeast Atlantic Ocean, to the British Isles, and the Norway coasts. This western boundary current is responsible for the mild **climate** of western **Europe**, which is located at a much higher **latitude** than most of New England, but experiences much milder **weather**.

The origin of the Gulf Stream goes back to the broad, slow, and warm North Equatorial Current under the trade winds, which moves to the west, and when it reaches the Caribbean Sea, its **water** moves through the Yucatan Channel. Here, it becomes not only narrower, but also gains strength, meandering around the Gulf of Mexico (here it is often referred to as the Loop Current), then exiting the Gulf at the Straits of Florida (here, it is called the Florida Current). Along the east coast of Florida, the current meets the Antilles Current, and the flow, now called the Gulf Stream, runs parallel to the coast until reaching Cape Hatteras, North Carolina, where it moves away from the coast. Around 50 degrees West, it splits into different currents, the largest of which is the North Atlantic Current, which also feeds the northbound Norwegian Current. The Canary Current flows towards the equator on the eastern side of the Atlantic Ocean.

The Gulf Stream also has mesoscale eddies or rings, large, concentric cylinders, reaching deep down in the water, which are usually about 62–186 mi (100–300 km) in diameter. They appear on both sides of the Gulf Stream, forming as a meandering loop cut off from the current, and can contain both a warm or a cold core. These rings help to maintain the termohaline (**temperature** and salinity) balance in the ocean basin.

The Gulf Stream not only helps to redistribute heat by carrying warm waters towards the North Pole, but also has a large impact on the climate on land by bringing humid, mild air to the British Isles and Northwest Europe, causing significantly milder winters than at the same latitudes in the West.

See also Ocean circulation and currents

GUYOT, ARNOLD HENRI (1807-1884)

Swiss geologist and geographer

Arnold Henri Guyot's geological field studies advanced the knowledge of **lakes**, **glaciers**, **ice ages**, mountains, erratic boulders, **evolution**, and **weather**.

Guyot was born in Boudevilliers, Switzerland, on September 28, 1807. After graduating from the University of Neuchâtel, Switzerland, in 1825, he went to Germany to continue his studies in botany, zoology, entomology, geography, and theology. While living and studying with botanist Alexander Braun (1805–1877) in Karlsruhe, Germany, he met naturalist **Louis Agassiz** (1807–1873) and botanist Karl Friedrich Schimper (1803–1867), who would later coin the term "ice age." During this time, Guyot considered becoming a minister, but decided instead on a career in science. He received his doctorate in **geology** from the University of Berlin in 1835 with a dissertation on lakes. Among his professors at Berlin was the geographer **Carl Ritter** (1779–1859).

For the next four years, Guyot worked as a private tutor for the family of the Count of Pourtalès-Gorgier in Paris and traveled throughout **Europe**. Reacquainted with Agassiz in Paris in 1838, Guyot became interested in glaciers, though he disagreed with Agassiz on many points of interpretation. They decided to collaborate on a study of Alpine glaciers, but through a misunderstanding between them, the resultant publication appeared under Agassiz's name alone in 1847. Guyot and Agassiz remained friends, but Guyot only received credit for his work on this project in the 1880s, after both his and Agassiz's deaths.

Pursuing research in botany, geology, geography, glaciology, **meteorology**, and **cartography**, Guyot taught history, natural history, and **physical geography** at the Neuchâtel Academy from 1839 until the Revolutions of 1848 closed that institution and deprived him of his livelihood. In consequence, he, Agassiz, and many other first-rate scientists immigrated to America. Lectures he presented at the Lowell Technological Institute in Boston, Massachusetts, published as *Earth and Man* in 1849, quickly established his reputation in the English-speaking world.

In 1854, Guyot became professor of geology and physical geography at Princeton University, where he remained until his death in Princeton, New Jersey, on February 8, 1884. He founded what became the Princeton Department of Geosciences in 1855 and the Princeton Museum of Natural History in 1856. Princeton named him the first John I. Blair professor of geology in 1864. During his summers on vacation from Princeton, Guyot conducted extensive on-site meteorological studies of the Appalachians from Mt. Katahdin, Maine, to Mt. Oglethorpe, Georgia, sponsored by the Smithsonian Institution. These explorations eventually led to the creation of the Appalachian Trail. He encouraged his student, William Berryman Scott (1858–1947), later the second Blair professor, to lead a dangerous expedition to Colorado to gather **fossils** in 1877.

The "guyot," a flat-topped undersea mountain, was named for him by the sixth Blair professor, **Harry Hammond Hess** (1906–1969). Also named in his honor are three mountains, one in New Hampshire, one on the North Carolina-Tennessee border, and one in Colorado, as well as Guyot Hall, the geology building at Princeton.

See also Evolution, evidence of; Glacial landforms; Glaciation; Moraines; Mountain chains; Weather forecasting methods; Rock

GUYOTS AND ATOLLS

A guyot is a flat-topped submarine mountain, or seamount, that once emerged above sea level as a volcanic island, and then resubmerged when volcanic activity ceased. **Erosion** by wave activity during submergence creates the characteristic flat-topped profile of a guyot. In some cases, carbonate reefs fringing an aging volcanic island continue to grow as the island sinks below sea level, leaving a circular island of coral, or an atoll, surrounding a round lagoon where the peak of the extinct **volcano** once stood. The British naturalist, Charles Darwin (1809–1882), observed atolls in the southwest Pacific Ocean during his nineteenth century travels aboard the *Beagle*, and he was the first to suggest that an atoll is a crown of coral on a newly-submerged guyot.

Seamounts are volcanic hills or plateaus formed by extrusion of **lava** onto the seafloor in places where plates of oceanic **lithosphere** override hot areas in the mantle near divergent plate tectonic boundaries called **mid-ocean ridges**, and over localized intraplate mantle upwellings called hot spots. Most seamounts never grow tall enough to become islands, but some very large ocean-floor volcanoes, particularly those above well-established **hotspots**, emerge above sea level before plate motion removes them from their magmatic sources. The Hawaiian Islands and Iceland are examples of oceanic islands created by vigorous hot spot volcanism.

After growth and emergence, large volcanic islands evolve through several stages of decline and submergence. The weight of a cooling volcanic construction depresses the lithosphere into an underlying plastic layer of the mantle called the

asthenosphere. When volcanic activity ceases or slows, the rate of depression, or isostatic subsidence, outpaces the rate of volcanic construction, and the island sinks. Wave erosion cuts a bench encircling the declining island, and carbonate organisms, including corals, construct a ring of shallow-water carbonate rocks around it. As subsidence and erosion continue, the peak of the extinct volcano is planed off, and a carbonate lagoon fills the flat wave-cut surface creating an atoll. Eventually, the atoll sinks below the biologically productive photic zone, and carbonate production ceases. Most tropical guyots have a carbonate cap, while most high-latitude guyots do not. Once the guyot has fully cooled, it reaches a state of isostatic equilibrium and stops subsiding. Plate motion then carries the guyot passively toward a **subduction zone** where it will eventually accrete to a continental margin or subduct into the mantle.

See also Isostasy

GYPSUM

Gypsum, a white mineral soft enough to be scratched with a fingernail, is hydrated calcium sulfate [$Ca(SO_4)\cdot 2H_2O$]. Gypsum often begins as calcium sulfate dissolved in an isolated body of salt **water**. As the water evaporates, the calcium sulfate becomes so concentrated that it can no longer remain in solution and crystallizes out (precipitates) as gypsum. Many large beds of gypsum have been formed in this way.

Gypsum occurs in a number of distinct forms, including a clear, parallelogram-shaped crystal (selenite); a white, **amorphous** form (alabaster, used for ornamental carving); and a fibrous, lustrous form (satin spar, used in jewelry). When ground up and heated to drive off its water, gypsum becomes a powder termed plaster of Paris. Plaster of Paris has the useful property of hardening in any desired shape when mixed with water, molded, and allowed to dry.

Gypsum is one of the most widely used **minerals** in the world. Some 90 countries mine gypsum, producing more than 100 million tons (91 million metric tons) annually. The construction industry has long been particularly gypsum intensive. In the late nineteenth and early twentieth centuries gypsum was widely used in plastering, which since the 1950s has been displaced by gypsum drywall (sheetrock). The average new U.S. home contains tons of gypsum drywall. Gypsum is also an ingredient in portland cement, which is used in the construction of bridges, buildings, highways, and the like, and millions of tons of gypsum are used annually as fertilizer. Small quantities of pure gypsum are essential in smelting, glassmaking, and other industries.

Low-grade gypsum is manufactured synthetically at coal-fired electric power plants as a by-product of pollution-control processes that remove sulfur from flue gas. Synthetic gypsum production exceeds 110 million tons (100 million metric tons) annually.

See also Mohs' scale

H

HAIL • *see* PRECIPITATION

HALF-LIFE

As defined by geophysicists, the half-life (or half-value period) of a substance is the time required for one-half of the atoms in any size sample to radioactively decay.

Radioactive elements have different isotopes that decay at different rates. As a result, half-life varies with regard to the particular isotope under consideration. Some isotopes have very short half-lives, for example oxygen-14 has a half-life of only 71 seconds, some are even shorter—with values measured in millionths of a second not being uncommon. Other elements' isotopes can have a much longer half-life, thallium-232 has a half-life of 1.4 x 10 ^{10} years and carbon-14 has a half-life of 5,730 years. This latter figure is used as the basis of radiocarbon dating.

While living, an organism takes in an amount of carbon-14 at a relatively constant rate. Once the organism dies no more carbon-14 is taken in and the amount of carbon-14 present overall starts to decrease, decreasing by half every 5,730 years. By measuring the ratio of carbon-12 to carbon-14 an estimate of the date when carbon-14 stopped being assimilated can be calculated. This figure can also be obtained by comparing the levels of **radioactivity** of the test material to that of a piece of identical material that is fresh. Other radioactive elements can be used to date older, inorganic materials (e.g., rocks).

Strontium-90 has a half-life of 29 years. If starting with a 2.2 lb (1 kg) mass of strontium-90, then after 29 years there will only be 1.11 lb (0.5 kg) of strontium-90 remaining. After a further 29 years there will only be 0.55 lb (0.25 kg). Strontium-90 decays to give yttrium-90 and one free electron. Half-life is independent of the mass of material present.

The half-life ($t_{1/2}$) of a material can be calculated by dividing 0.693 by the decay constant (which is different for different radionucleotides). The decay constant can be calculated by dividing the number of observed disintegrations per unit time by the number of radioactive nuclei in the sample. The decay constant is usually given the symbol k or λ.

The half-life of a material is a measure of how reactive it is either in terms of radioactive decay or in participation in specific reactions.

See also Atomic mass and weight; Atomic number; Atomic theory; Cosmic microwave background radiation; Dating methods; Geologic time

HALLEY, EDMOND (1656-1743)

English astronomer

The son of a wealthy merchant, Edmond Halley was attracted to **astronomy** after seeing two **comets** as a child. By the age of eighteen, he had found errors in authoritative tables on the positions of Jupiter and Saturn and by nineteen, had published a paper on the laws of **Johannes Kepler**. In 1676, Halley left England for St. Helena, an island west of **Africa**, to map the southern constellations, a task never before undertaken. Although the **climate** of St. Helena proved less than ideal for Halley's purposes, he was able to catalogue 341 stars before returning to England. His pioneering work on the island assured his place in England's scientific community, and Halley was awarded a master's degree from Oxford as well as election to the Royal Society.

In 1684 Halley entered into a conversation with biologist Robert Hooke and architect Christopher Wren (1632–1723) that concerned the force that drove the movement of the planets. Unable to reach a satisfactory conclusion, Halley turned to his friend Isaac Newton. Discovering that Newton had already answered the question using his law of **gravity**, Halley convinced his reticent friend to publish his findings. Using funds bequeathed to him by his father, Halley financed the publication of *Mathematical Principles of Natural Philosophy*, now considered one of the classic texts of modern scientific thought.

At the age of 39 Halley turned his attention to comets, which, as they streaked unexpectedly through the sky, appeared ungoverned by Newton's law. Halley, however, believed that gravity did indeed dictate their path and that the rarity of their appearances was due to the vast length of their orbit, which was elliptical. With the help of Newton, Halley compared the paths of past comets that had appeared in 1531, 1607, and 1682. From this data he was able to determine that these seemingly separate comets were indeed the same comet and accurately predicted its reappearance in 1758. In 1705, Halley published his findings in *A Synopsis of the Astronomy of Comets*. Eventually, the comet that he predicted was named for him.

In addition to his findings concerning comets, Halley undertook a lengthy study of solar eclipses and discovered that the so-called fixed stars actually moved with respect to each other. He also wrote in favor of the theory that the universe is limitless and has no center. Halley's scientific interests, however, extended beyond astronomy. He played a major role in transforming the Royal Society from a social club into a well-respected clearing-house for scientific ideas. He devised the first **weather** map and calculated the amount of salt deposited by **rivers** into seawater over millions of years which allowed him to draw conclusions about the age of Earth. He also invented, developed, and tested one of the first practical diving bells. He served as chief science advisor to Peter the Great when the Russian czar came to England in an attempt to integrate Western advances into his country's society. From 1698 to 1700, Halley commanded the *Paramour*, a Royal Navy ship, for a scientific expedition which studied the effects of the Earth's **magnetic field** on magnetic needle compasses. He became Astronomer Royal in 1720, and continued to make astronomical observations and attend scientific meetings until shortly before his death in Greenwich at the age of 86.

HARRISON, JOHN (1693-1776)

English clockmaker and carpenter

John Harrison solved the so-called "longitude problem," that is, he developed the means to enable navigators to calculate their east-west (longitudinal) positions at sea. A ship's north-south (latitudinal) position is easily computed from the **Sun**, stars, date, and local time, but to calculate longitudinal position a navigator must also know the current time at the home port and compare it with the local time of the ship as determined by observing the Sun and stars. This calculation is based on the fact that every hour represents 15 degrees of **longitude**. The principle was known centuries before Harrison, but using it was not possible in practical navigation until he invented his portable, durable, and extremely accurate clock, which proved reliable under the harsh conditions of the sea.

Born the son of a carpenter on March 24, 1693, in Foulby, Yorkshire, England, Harrison early learned his father's trade as well as surveying, clockmaking, bell tuning, and several other practical skills. He also enjoyed music and was a singer. The family moved to Barrow-on-Humber, Lincolnshire, while Harrison was still a child. In the 1720s, he began a professional association with his brother James, born in 1704. Together until 1739, they designed and built beautiful, precise, reliable clocks, soon renowned as the most accurate in Britain.

As the world's dominant sea power from the end of the sixteenth century until the middle of the nineteenth, Britain was keenly aware of the longitude problem and was quite serious about solving it. In 1675, King Charles II founded the Royal Observatory at Greenwich, England, mainly to gather data for the longitude problem. In 1714, the British Parliament passed the Queen Anne Act, which offered a prize of £20,000 (about £1,932,917 in 2001 British money or $2,811,860 in 2001 American money) to anyone who could calculate a ship's longitude to within a half-degree throughout its voyage from Britain to the West Indies. Many tried and failed to win that prize.

Fixed on winning the prize, Harrison began working on the longitude problem in 1730 and submitted his first sea clock, known as the H1 chronometer, to the Board of Longitude in London in 1736. On the basis of H1's partial success, the Board gave him financial assistance to continue his research. From 1737 to 1740, he worked on a larger instrument, H2, but it failed. His experiments with H3 from 1740 to 1749 also ended in failure. In 1755, he stumbled across an entirely different design for H4, similar to a pocket watch. The test results of H4 on the voyage of the *Deptford* to Jamaica in 1761–62 and on the voyage of the *Tartar* to Barbados in 1764 exceeded the stipulations of the Queen Anne Act.

Despite the success of H4, the Board of Longitude awarded Harrison only £10,000. The Royal Astronomer Nevel Maskelyne (1732–1811), even though he was aboard the *Tartar* during the trial of H4, remained unconvinced that any timepiece could be a more accurate indicator of longitude than the popular "lunar distance method," by which navigators computed longitude from their observations of the Moon's position relative to selected stars, according to tables prepared by the Royal Observatory. Maskelyne was jealous of Harrison, whom he spurned as a mere "mechanic," and changed the rules of the contest to favor astronomers.

Harrison, with his son William, spent the rest of his life trying to claim the second half of his prize. The Board was adamant about not giving it to him but, in 1773, after Harrison appealed to King George III, Parliament grudgingly recognized his having solved the longitude problem and gave him an additional £8,750. All four of his marine chronometers are now in the National Maritime Museum, London. He died in London on his birthday in 1776.

See also History of exploration II (Age of exploration); Latitude and longitude; Time zones

HAUPTMAN, HERBERT A. (1917-)

American mathematician and biophysicist

In the early 1950s, Herbert A. Hauptman and former classmate, Jerome Karle, developed a mathematical system, usually referred to as the "direct method," for the interpretation of data on atomic structure collected through x-ray crystallography. The system, however, did not come into general use until the l960s, and it was only in 1985 that Hauptman and Karle were jointly awarded the Nobel Prize in chemistry for their accomplishment.

Hauptman and Karle developed a complex series of mathematical formulas, relying heavily on probability theory, which made it possible to correctly infer the phases from the data that was recorded on the photographic film. Their new mathematical system came to be known as the determination of molecular structure by "direct method." They demonstrated the workability of their new technique in 1954 by calculating by hand, in collaboration with researchers at the United States Geological Survey, the atomic structure of the mineral colemanite.

Herbert Aaron Hauptman was born in New York City on February 14, 1917, the son of Israel Hauptman, an Austrian immigrant who worked as a printer, and Leah (Rosenfeld) Hauptman. He grew up in the Bronx and graduated from Townsend Harris High School. At the City College of New York, he majored in mathematics and received a Bachelor of Science degree in 1937. Karle, his later collaborator, also graduated from City College the same year. Hauptman went on to complete a master's degree in mathematics at Columbia University in 1939. He married Edith Citrynell, a schoolteacher, on November 10, 1940; they eventually had two daughters. Hauptman worked for two years as a statistician in the United States Bureau of the Census before serving in the United States Army Air Force from 1942 to 1947. After his period of service ended, Hauptman went to work as a physicist and mathematician at the Naval Research Laboratory in Washington, remaining there until 1970. While working at the laboratory, he enrolled in the doctoral program in mathematics at the University of Maryland and received his Ph.D. in 1955.

At the Naval Research Laboratory, Hauptman renewed his acquaintance with Karle, who had come to the laboratory in 1946. The two men soon began to work together on the problem of determining molecular structures through the methodology of x-ray crystallography. Most of the work that later led to their joint Nobel Prize was done between 1950 and 1956. A brief monograph, *Solution of the Phase Problem, 1. The Centrosymmetric Crystal,* was published in 1953 that revealed many of the results of their studies.

The German physicist Max Laue had discovered as far back as 1912 that it was possible to determine the arrangement of atoms within a crystal by studying the patterns formed on a photographic plate by x rays passed through a crystal. Since that time x-ray crystallography had become a standard tool for chemists, physicists, geologists, biologists, and other scientists concerned with determining the atomic structure of substances. X-ray crystallography, for example, had made possible the discovery of the double-helical structure of deoxyribonucleic acid (DNA) by molecular biologists Francis Crick, James Watson, and others in the 1950s. The problem with the technique was that interpreting the patterns on the photographic plates was a difficult, laborious, and time-consuming task. The accurate determination of the atomic structure of a single substance could require one or more years of work based upon indirect inferences that often amounted to educated guesswork. The greatest difficulty arose from the fact that while photographic film could record the intensity of the x-ray dots that formed the patterns, it could not record the phases (the minute deviations from straight lines) of the x rays themselves.

Hauptman and Karle's system met with a good deal of skepticism and resistance from the specialists in x-ray crystallography in the 1950s and was largely ignored for about ten years. This was partly due to the fact that most crystallographers of the time lacked the mathematical knowledge and sophistication to make use of the new technique. It also stemmed from the fact that the necessary mathematical calculations themselves were a laborious process. It was the introduction of computers and the development of special programs to deal with the Hauptman-Karle method in the 1960s that finally led to its widespread acceptance and use. The work that originally required months or years to complete could now be done in a matter of hours or, at most, days. By the mid 1980s the atomic structures of approximately 40,000 substances had been determined through use of the direct method, as compared to only some 4,000 determined by other methods in all the years prior to 1970, and some 4,000 to 5,000 new structures were being determined each year.

Hauptman left the Naval Research Laboratory in 1970 to become head of the biophysics laboratory at the Medical Foundation of Buffalo, a small but highly regarded organization specializing in research on endocrinology. He also became professor of biophysical science at the State University of New York at Buffalo. Hauptman served as executive vice president and research director of the Medical Foundation from 1972 to 1985 and president from 1985 onwards. There he worked to perfect the direct method and to extend its use to the study of very large atomic structures. Hauptman has received numerous awards, including the 1985 Nobel Prize in chemistry shared with Karle, the Award in Pure Sciences from the Research Society of America in 1959, and, also with Karle, the A. L. Patterson Memorial Award of the American Crystallography Association in 1984.

See also Atomic theory; Crystals and crystallography; Geochemistry; Industrial minerals; Mineralogy

HAWAIIAN ISLAND FORMATION

The Hawaiian archipelago is a group of 132 islands, reefs, and shoals in the North Pacific Ocean that extends about 1,525 mi (2,454 km) from Kure Atoll (29°N, 178°W) to the big island of Hawaii (19°N, 156°W). This string of geographically remote and geologically unique volcanic islands makes up the U.S. state of Hawaii, and includes the eight main Hawaiian Islands of Ni'ihau, Kauai, Oahu, Molokai, Lanai, Maui, Kahoolawe, and Hawaii. The islands are progressively younger in geologic age toward the southeast; Kauai and Ni'ihau are about 5 million years in age, and the big island of

Hawaii is less than 0.5 million years old. Indeed, new volcanic rocks are being deposited at Mt. Kilauea on Hawaii today.

The Hawaiian Islands are the exposed summits of the southernmost seafloor mountains, or seamounts, in the Hawaiian-Emperor seamount chain. This 3,105 mi (5,750 km) line of 107 volcanoes has formed over the last 70 million years as the Pacific Lithospheric Plate has moved to the northwest over a stationary magmatic hot spot in the mantle. Each individual **volcano** in the seamount chain formed as heat from the Hawaiian hot spot melted the overlying oceanic **crust**, and generated buoyant molten **rock**, or **magma**, which migrated upward and erupted onto the seafloor as **lava**. Many sequential lava flows then amalgamated to form seamounts composed mainly of an **iron** and magnesium-rich, or **mafic**, volcanic rock called **basalt**. Eventually, some of these seamounts grew tall enough to emerge above sea level. The Hawaiian-Emperor seamounts are examples of basaltic volcanoes with low-angle slopes and wide bases, called shield volcanoes. Mauna Loa, the central volcanic peak on Hawaii, is the world's tallest and most massive mountain when measured from its submarine base. It has a total elevation of about 32,000 ft (10 km), and its base covers an **area** about the size of the U.S. state of Connecticut.

Ongoing northwestward migration of the Pacific Plate at 3.4 in/year (9 cm/yr) has carried all but the newest Hawaiian-Emperor seamounts away from the hot spot. As a seamount moves away from the hot spot, volcanic activity ceases, its rock base cools, and it begins to subside into the surrounding ocean crust. An aging oceanic island then sinks below sea level, and wave **erosion** levels off the volcanic peak, creating a flat-topped seamount called a guyot. Sometimes, **coral reefs** fringing a volcanic island continue to grow after the island has subsided below sea level, creating a ring-shaped carbonate island called an atoll, or annular island. English naturalist Charles Darwin (1809–1882) first suggested this explanation for the formation of atolls during the voyage of the HMS *Beagle* from 1831 to 1836.

By this mechanism of sequential island formation and subsidence, the Hawaiian hot spot has perforated the Pacific Plate with a line of volcanoes that are younger and higher toward the southeast. The Hawaiian-Emperor Chain propagated northward, beginning at least 70 million years ago, the age of the Meiji seamount at the Aleutian Trench. About 40 million years ago, a dogleg bend in the chain suggests a shift to northwestward plate motion, possibly due to the collision of the Indian subcontinent with **Asia** that created the Himalayan Mountains at that time. Since 40 million years ago, the Pacific Plate has moved northwest, bringing the hot spot to its present position beneath the southern shore of the island of Hawaii. The newest volcano in the Hawaiian-Emperor Chain, the Lo'ihi seamount, is presently forming on the seafloor about 25 mi (40 km) southeast of Hawaii.

Today, geologists at the Hawaiian Volcano Observatory at Mt. Kilauea, and visitors to Hawaii Volcanoes National Park, can observe active **volcanic eruptions**. Low-viscosity basaltic lava erupts from volcanic vents at about 1,830°F (1,000°C). The surface of fast-flowing lava streams cools to create a ropy-textured skin called *pahoehoe*. (*Pahoehoe* means "rope" in Hawaiian.) After the surface of a flow has cooled, lava may continue to move beneath the surface in lava tubes. Sometimes, dissolved volatile gases escape during cooling, and the lava forms a jumble of sharp blocks called *aa*. When lava flows into the ocean, it cools very rapidly to form pillow basalt, the most common submarine basaltic texture. The Hawaiian Islands are the world's best natural laboratory for the study of hot spot dynamics, basaltic volcanism and ocean island formation.

See also Volcanic eruptions; Volcanic vent

HAWKING, STEPHEN (1942-)

English physicist

Stephen Hawking has been called the most insightful theoretical physicist since **Albert Einstein**. His work concentrates on the puzzling cosmic bodies called black holes and extends to such specialized fields as particle **physics**, supersymmetry, and quantum **gravity**. The origin and fate of the universe are a central concern of Hawking's work. Though few people are able to understand the intricacies of these abstruse subjects, Hawking has gained a worldwide following, not only among other scientists, but also among a great many laypeople. As an author and lecturer, he has achieved celebrity status.

Stephen William Hawking was born in Oxford, England. He often refers to the fact that his birth date coincided with the 300th anniversary of Galileo Galilei's death. Hawking was the eldest child of an intellectual and accomplished family. His father, Frank Hawking, was a physician and research biologist who specialized in tropical diseases; his mother, Isobel, the daughter of a Glasgow physician and a well-read, lively woman, was active for many years in Britain's Liberal Party

Stephen Hawking's earliest years were spent in Highgate, a London suburb. In 1950, when he was eight, the family moved to St. Albans, a cathedral town some twenty miles northwest of London. Two years later, his family enrolled him in St. Albans School, a private institution affiliated with the cathedral. As Michael White and John Gribbin describe the young schoolboy in *Stephen Hawking: A Life in Science*, "He was eccentric and awkward, skinny and puny. His school uniform always looked a mess and, according to friends, he jabbered rather than talked clearly, having inherited a slight lisp from his father." Young Hawking's abilities made little impact on his teachers or fellow students. But he already knew he wanted to be a scientist, and by the time he reached his middle teens, he had decided to pursue physics or mathematics.

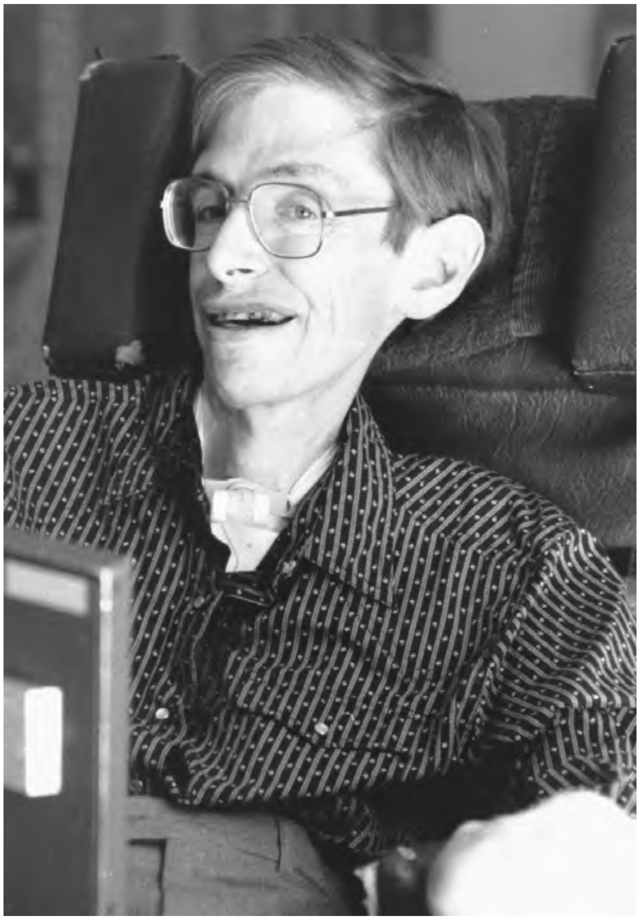
Gangly and unathletic, Hawking formed close friendships with a small group of other precocious boys at school. Intrigued by subjects that focused on measurable quantities and objective reasoning, Hawking began to show increasing skill at mathematics, and soon he was outdistancing his peers with high grades while spending very little time on homework. In 1958, Hawking and his friends built a primitive computer that actually worked. In the spring of 1959, Hawking won an open scholarship in natural sciences to University College, Oxford—his father's old college—and in October he enrolled there. It was at Oxford that his unusual abilities began to become more obvious. Hawking's ease at handling difficult problems made it seem to others that he didn't need to study. In *Stephen Hawking's Universe*, John Boslough wrote, "He took an independent and freewheeling approach to studies although his tutor, Dr. Robert Berman, recalls that he and other dons were aware that Hawking had a first-rate mind, completely different from his contemporaries."

In 1962, after receiving a first-class honors degree from Oxford, Hawking set off for Cambridge University to begin studying for a Ph.D. in **cosmology**. Now he was beginning to deal with some of the themes that would preoccupy him throughout his life. One of these was the poorly understood question of black holes. As scientists were later to realize, a black hole is a cosmic body that by its very nature can never be seen. One type of black hole is thought to be the remnant of a collapsed star, which possesses such intense gravity that nothing can escape from it, not even light. Hawking was also intrigued by "space-time singularities," those phenomena in the physical universe or moments in its history where physics seems to break down. In attempting to understand a black hole and the space-time singularity at its center, Hawking made pioneering studies, using formulas developed more than half a century earlier by Einstein.

Hawking received his Ph.D. in 1965 and obtained a fellowship in theoretical physics at Gonville and Caius College, Cambridge. He continued his work on black holes, frequently collaborating with Roger Penrose, a mathematician a decade his senior, who like Hawking was deeply interested in theories of space-time. Though still in his twenties, Hawking was beginning to acquire a reputation, and he would often attend conferences where he shocked people by questioning the findings of eminent scientists much older than himself.

In 1968, Hawking joined the staff of the Institute of Astronomy in Cambridge. He and Penrose began using complex mathematics to apply the laws of thermodynamics to black holes. He continued to travel to America, the Soviet Union, and other countries, and in 1973, he published a highly technical book, *The Large Scale Structure of Space-Time*, written with G. F. R. Ellis. Not long afterward, Hawking made a startling discovery: whereas virtually all previous thinking assumed that black holes could not emit anything, Hawking theorized that under certain conditions they could emit subatomic particles. These particles became known as Hawking Radiation.

Early in 1974, at the unusually young age of 32, Hawking was named a fellow of the Royal Society. Soon afterward, he spent a year as Fairchild Distinguished Scholar at the California Institute of Technology in Pasadena. On returning to England, he continued to work toward a theory of the origin of the universe. In this endeavor, he made progress toward linking the theory of relativity, which deals with gravity, with quantum mechanics, which deals with minuscule events inside the **atom**. Such a theoretical linkage, long sought by researchers, is called the Grand Unification Theory. In 1978, Hawking received the Albert Einstein Award of the Lewis and Rose Strauss Memorial Fund, the most prestigious award in theoretical physics. The following year he co-edited a book with Werner Israel, called *General Relativity: An Einstein Centenary Survey*. In 1979, Hawking was named Lucasian Professor of Mathematics at Cambridge—a position held three centuries earlier by **Sir Isaac Newton**. In the 1980s, his work was beginning to lead him to question the **big bang theory**, which most other scientists were accepting as the probable origin of the universe. Hawking now asked whether there really had ever been a beginning to space-time (a big bang), or whether one state of affairs (one universe, to put it loosely) simply gave birth to another without beginning or end. Hawking suggested that new universes might be born frequently through little-understood anomalies in space-time. He also investigated string theory and exploding black holes, and showed mathematically that numerous miniature black holes may have formed early in the history of our universe.


Stephen Hawking. ***AP/Wide World. Reproduced by permission.***

In 1988, Hawking's *A Brief History of Time: From the Big Bang to Black Holes* was published. Intended for a general audience, it leapt onto best-seller lists in both America and Britain and remained there for several years. In that book, Hawking explained in simple language the evolution of his own thinking about the cosmos. Major articles followed in *Time*, *Popular Science*, and other magazines; films and television programs featured Hawking. He received honorary degrees from many institutions, including the University of Chicago, Princeton University, and the University of Notre Dame. His numerous awards included the Eddington Medal of the Royal Astronomical Society, in 1975; the Pius XI Gold Medal, in 1975; the Maxwell Medal of the Institute of Physics, in 1976; the Franklin Medal of the Franklin Institute, in 1981; the Gold Medal of the Royal Society, in 1985; the Paul Dirac Medal and Prize, in 1987; and the Britannica Award, in 1989.

In 1965, Hawking married Jane Wilde, and they had two sons and a daughter. The couple separated in 1990. Hawking suffers from amyotrophic lateral sclerosis, also called Lou Gehrig's disease, which confines him to a wheelchair and requires him to use a computer and voice synthesizer to speak.

HELIOCENTRIC MODEL • *see* ASTRONOMY

HERSCHEL, CAROLINE LUCRETIA

(1750-1848)

German astronomer

Caroline Herschel was the first female astronomer to discover a comet. Herschel grew up in a home where her father encouraged learning, much to the displeasure of her mother, who believed girls should focus their education solely on skills necessary to manage a well-appointed traditional home. After her father's death in 1767, Herschel's formal education in mathematics and science ceased, as she ceded to the wishes of her mother. Finally, in 1772, Herschel left Germany to pursue a musical career in Bath, England, living with her brother, the astronomer William Herschel.

In England, Herschel trained to become a professional singer, but she also began to study mathematics under her brother's tutelage. William Herschel soon involved her in his hobby, **telescope** building. She helped him grind and polish mirrors for his telescopes, while copying catalogs and tables for his reference. After he discovered the planet Uranus in 1781, William Herschel was awarded a yearly stipend by King George III that allowed him and his sister to pursue **astronomy** full time.

As she became more proficient with her own telescope, Herschel made a name for herself in this largely male domain. In 1783, she discovered three new nebulas and from 1786–1797, she discovered eight **comets**. George III awarded her a salary as well, a rare gesture at the time. She also took on the formidable task of making a thorough index of the star catalog created by John Flamsteed (1646–1719), the first Royal Astronomer. This job called for perseverance, accuracy, and attention to detail, all qualities in which Herschel excelled.

Following her brother's death, Herschel returned to Hanover, Germany, but remained in close contact with her brother's son, astronomer John Herschel (1792–1871), for whom she compiled a new catalog of nebulae. Herschel and Scottish scientific writer Mary Somerville (1780–1872) became the first women to be awarded an honorary membership in the Royal Society. In spite of her informal training, Herschel became a well-known figure in her own time and an important figure in the history of astronomy.

HERSCHEL, SIR WILLIAM (1738-1822)

German-born English astronomer

Sir William Herschel was among the preeminent astronomers of the eighteenth century, and is credited with discovering the planet Uranus, binary stars, nebulae, and for correctly describing the form of the Milky Way galaxy.

Herschel was born in Hanover, Germany at a time when the city belonged to England under the rule of George II. As Herschel's father was a musician in the Hanoverian army, Herschel himself was trained in music in order to enter the same profession. The Seven Years' War, however, made military life an unattractive option, and in 1757, Herschel arrived in England where he began working as an organist and music teacher. Herschel learned of **astronomy** through his interest in the theory of music and the scientific basis for musical sounds, which led him to mathematics and then optics.

Newton's treatise on optics inspired Herschel with his desire to study the stars. Unable to find a **telescope** of a high enough resolution, he decided to grind his own lenses and to design his own instruments. With his first telescope, a 6-foot Gregorian reflector that was one of the best of its kind, he decided that its first application would be to conduct a systematic survey of the stars and planets. Herschel was assisted in this endeavor by his sister Caroline, who also discovered eight **comets** and produced two astronomy catalogues in her lifetime. Throughout his life, Herschel built numerous telescopes, each one more sophisticated and more powerful than the last.

Herschel's first major discovery occurred in 1781, during his second survey of the sky when he announced the existence of a new planet to be found in the constellation of Taurus. Herschel's name for the new planet was *Georgium Sidus*, George's star, in honor of King George III, but it eventually came to be known as Uranus, after the mythical father of Saturn. The discovery of Uranus, which effectively doubled the previously accepted size of the **solar system**, caused a popular and scientific sensation, and George III appointed Herschel to the position of King's Astronomer while providing him with a small annuity that allowed him to pursue astronomy full time.

Herschel's most significant achievements were in the **area** of sidereal astronomy, to which he contributed the first systematic body of evidence on the order and nature of the stars and the planets. Whereas plenty of theories had been put forward by prominent philosophers of the time on the systems that might govern the universe, none were supported by any scientific gathering of data. In 1783, Herschel began to search for nebulae in the sky, and raised their known total from little more than 100 to 2,500. Much of eighteenth-century astronomy set out to determine the distances between stars; trigonometrical calculations based on their apparent annual movement, however, had failed. **Galileo Galilei** had proposed the use of double stars, pairs of stars very close together, to calculate stellar distance, where the fainter member of the pair was so far away as to represent a fixed point from which the annual movement of its brighter companion could be measured. In Herschel's second survey, he searched for double stars, producing three catalogs over the next 40 years and listing 848 examples. It was later discovered by another astronomer who had seen Herschel's work that these double stars were in fact companions in **space** held together by gravitational forces and therefore equidistant from the earth; Herschel had assumed that companions in space would have been of equal brightness, and had therefore discounted this possibility. Nonetheless, much of Herschel's work was concerned with producing evidence for the powers of attraction between stars. In three of his papers delivered between 1784 and 1789, he proposed a cosmogony for the universe in which stars, initially randomly scattered throughout the universe, clustered together over time around the regions from which they originally developed.

Herschel was the first to embark upon a scientific study of the Milky Way and half of his work, though less influential, focuses upon the solar system. He studied the **Sun**, observing that what we see is not the Sun itself but the **clouds** of gases that cover its surface, and examined the nature of the infrared section of the spectrum by which some of the Sun's heat is transmitted. Besides calculating the height of lunar mountains, Herschel devoted most of his attention to the other known planets, Venus, Mars, Jupiter, and Saturn, determining their **rotation** period and checking the inclination of their axes, their shape, and the nature of their atmospheres. Herschel devoted most of his attention to examining Saturn and its rings, arguing at one point that the rings were solid, but later conceding that they were in fact composed of floating particles.

Herschel's work on nebulae had led him to conclude that they might well be other solar systems seen only as a luminous cluster of stars around a brighter one. As a result, he saw the Milky Way and Earth as only one rather insignificant part of the universe. In this sense, he changed the status of the solar system within the universe in much the same way as **Nicolas Copernicus** had the earth when he showed that the planets revolved around the Sun rather than Earth.

See also Cosmology

HESS, HARRY HAMMOND (1906-1969)

American geologist

Harry Hammond Hess spent much of his career studying what the ocean floor was made of and where it came from. He was a renowned geologist whose interests and influence ranged from **oceanography** to **space** science. One of Hess's most important contributions to science was the concept of seafloor spreading, which became a cornerstone in the acceptance of the **continental drift theory** during the 1960s. As an officer in the United States Naval Reserve, he was able to combine military service with scientific investigation; in his later years, he became an important figure in NASA, helping direct the science of lunar exploration.

Hess was born in New York City to Julian S. Hess, a member of the New York Stock Exchange, and Elizabeth Engel Hess. He attended Asbury Park High School in New Jersey before entering Yale University in 1923. At Yale, he intended to study electrical engineering, but changed his mind and graduated in 1927 with a B.S. degree in **geology**. Hess then spent two years in northern Rhodesia (now Zambia) as an exploration geologist. Returning to the United States, Hess received his doctorate from Princeton University in 1932. He taught at Rutgers University for a year, conducted research at the Geophysical Laboratory at the Carnegie Institute of Washington, and then returned to Princeton in 1934. Hess would remain at Princeton for essentially the rest of his career, serving as chair of the university's geology department from 1950 to 1966.

Annette Burns, daughter of a botany professor at the University of Vermont, became Hess's wife in 1934. She was a source of strong support for Hess throughout his life, and accompanied him to conferences and scientific meetings. The couple had two sons.

As a professor at Princeton, Hess continued his work on mountain ranges and **island arcs**, which are arc-shaped chains of islands that usually contain active volcanoes. By 1937, he had developed a unifying hypothesis that tied together the creation of island arcs with the presence of **gravity** anomalies and magnetic belts of serpentine (a **rock** which is formed by the crystallization of **magma**).

Hess's geological research was halted during World War II because he was a reserve officer in the Navy. He was initially assigned to duty in New York City, where he was responsible for estimating the positions of enemy submarines in the North Atlantic. Hess was then assigned to active sea duty and eventually became commander of an attack transport ship. This vessel carried equipment for sounding the ocean floor, and Hess took full advantage of it. He mapped a large part of the Pacific Ocean, discovering in the process the underwater flat-topped seamounts that he named **guyots**, in honor of A.H. Guyot, the first professor of geology at Princeton. The origin of guyots was puzzling, for they were flat on top as if they had been eroded off at the ocean surface, yet were two kilometers below sea level. As commander of the USS *Cape Johnson*, Hess also participated in four major combat landings, including one at Iwo Jima. Remaining a reserve officer after the war, Hess was called on for advice in such emergencies as the Cuban missile crisis in October 1962. By the time of his death he had achieved the rank of rear admiral.

After the war ended, Hess continued to study guyots as well as midocean ridges, which run down the centers of the Atlantic and Pacific **Oceans** like an underwater backbone. He also continued his mineralogical studies on the family of pyroxenes, an important group of rock-forming **minerals**. In 1955, he proposed that the boundary between the **crust** and the mantle of the earth is due to a change in the chemical composition of rocks.

During the 1950s, Hess became an influential backer of the ill-fated "Project Mohole," which proposed to drill a hole through the shallow oceanic crust into the earth's mantle for scientific sampling. In 1961, an experimental hole was bored through 11,600 ft (3,535 m) of **water**, 600 ft (183 m) of sediments, and 44 ft (13 m) of **basalt**. President John F. Kennedy telegraphed his congratulations to the National Science Foundation; John Steinbeck wrote an article for *Life* magazine about it. Despite amassing 25 million dollars in federal funding, Project Mohole foundered in 1966 under rising costs and political intrigue. It did, however, become an important stepping stone for the Deep Sea Drilling Project, successfully begun in the late 1960s.

Hess accepted visiting professorships at South Africa's Capetown University from 1949 to 1950, and at Cambridge University in 1965. Otherwise, he remained at Princeton until his death. He received numerous awards and honors, both at home and abroad, and was a major figure in the American Miscellaneous Society, a loosely-gathered group of scientists from different fields who liked to discuss "miscellaneous" ideas, such as Project Mohole.

From 1962 until his death, Hess chaired the Space Science Board that advised NASA on its lunar exploration program. He lived long enough to see the first person walk on the **Moon** in July 1969. One month later, while attending a space science conference in Woods Hole, Massachusetts, Hess died even as he was consulting a doctor about chest pains that he was experiencing.

Hess made a major contribution to the continental drift theory, which viewed continental and oceanic positions as the result of the break up of a single "supercontinent" (a theory first proposed by **Alfred Wegener** in 1912). Suggesting a mechanism by which continents could move away from each other without tearing up a rigid seafloor, Hess managed to unite several disparate elements: the youth of the ocean floor, the origin of midocean ridges, and the presence of island arcs and deep sea trenches surrounding the Pacific.

Hess's hypothesis gave geologists their first clue that drifting continents are carried passively on the spreading seafloor. In 1963, Fred Vine and **Drummond Matthews** at Cambridge University proposed a corollary to Hess's hypothesis: if the seafloor is created at the midocean ridges and spreads outward—and if the earth's **magnetic field** reverses polarity every few thousands of years—then the seafloor should be made of magnetized strips running parallel to the midocean ridges, alternating between normal and reverse polarity. Their idea, proposed independently by Lawrence Morley of the Geological Survey of Canada, was confirmed a few years later when scientists found the underwater bands of differently-magnetized rocks.

This oceanographic data established that continental drift does in fact occur. Over the next couple of years, geologists eventually accepted the new and revolutionary idea. Although certain details of Hess's seafloor spreading hypothesis have become outdated, its central idea—that seafloor is created at ridges and destroyed under continents—has become an important foundation of modern **earth science**.

HILDEBRAND, ALAN RUSSELL (1955-)

Canadian geologist

Alan Russell Hildebrand is part of the Geological Survey in Canada and The Geology and Geophysics Department at the University of Calgary. Hildebrand's greatest accomplishment in the field of geology includes the discovery of the catastrophic Chicxulub Crater in the Yucatan Peninsula of Mexico that is considered the site of the catastrophic event that resulted in the extinction of the dinosaurs. Additionally, Hildebrand is one of the leaders for the **Prairie** Meteorite Search and is a member of the Meteorites and Impacts Advisory Committee.

Alan R. Hildebrand began his career in geology after receiving his bachelor's degree in geology at the University of New Brunswick in 1977. Initially, Hildebrand worked in the mineral exploration industry. Eventually Hildebrand returned to school to seek his Ph.D. in planetary sciences. As part of his dissertation, Hildebrand discovered the Chicxulub crater in the Yucatan Peninsula of Mexico. In 1992, he received his Ph.D. from the University of Arizona. In 1999, he became a member of the faculty in the Department of Geology and Geophysics at the University of Calgary and currently holds a Canada Research Chair in Planetary Sciences. Additionally, Hildebrand is a research scientist for the Geological Survey of Canada, with his research focusing mainly on the **K-T event** as well as meteorite processes and impacts.

It has been theorized that the dinosaurs became extinct 65 million years ago by a disaster that has become known as the K-T event (Cretaceous-Tertiary Mass Extinction event). Presumably an asteroid hit the earth, its impact killing 70% of the species on Earth. In 1990, Alan Hildebrand discovered the Chicxulub Crater in the Yucatan Peninsula of Mexico. The crater has a diameter of 112 mi (180 km) and has been dated at about 65 million years ago. The asteroid that is responsible for creating the Chicxulub Crater is believed to have had a diameter of 6 mi (10 km).

Alan Hildebrand is currently one of the leaders for the Prairie Meteorite Search, a national project that focuses on the discovery of meteorites by prairie farmers. Researchers involved in the project travel to prairie farms to instruct locals on what meteorites look like and examine specimens found by the farmers. Additionally, Hildebrand volunteers for the Meteorites and Impacts Advisory Committee to the Canadian Space Agency. This committee is responsible for discovering meteorites around Canada and investigates possible fireballs.

See also K-T event; Meteoroids and meteorites; Cretaceous Period

HISTORICAL GEOLOGY

All areas of geologic study are subdisciplines of either historical **geology**, which focuses on the chemical, physical, and biological history of Earth, or physical geology, which is the study of Earth materials and processes. Historical geology uses theory, observation, and facts derived from studying rocks and **fossils** to learn about the **evolution** of Earth and its inhabitants.

According to the principle of **uniformitarianism**, most physical and chemical processes occurring today are very similar to those that operated in the geologic past, although their rates may be different. Therefore, by studying modern geologic activities and their products, geologists can understand how these activities produced the ancient **rock** record. In other words, the present is the key to the past. The principle of uniformitarianism has been very useful in deciphering much of the rock record.

Studies in historical geology rely on the rock record for factual information about Earth's past. As geologists collect data, they develop hypotheses to explain phenomena they observe. Geologists test hypotheses by making further observations of rocks and the fossils they contain. If this and other research supports a hypothesis, eventually it will be accepted as a theory explaining how Earth, and the life on it, evolved through time.

Rocks preserve a record of the events that formed them. The trained observer can examine the physical, chemical, and biological characteristics of a rock and interpret its origin. Fossils are an especially useful type of biological evidence preserved in **sedimentary rocks** (they do not occur in igneous or metamorphic rocks). Organisms thrive only in those conditions to which they have become adapted over time. Therefore, the presence of particular fossils in a rock provides paleontologists with very specific insights into the environment that formed that rock.

In addition to body fossils, sediments also preserve a variety of tracks and trails (for example, footprints, burrows, etc.). These biological impressions preserve traces of the daily activities of organisms, rather than their bodies, and so are called trace fossils. These too provide important clues to certain aspects of Earth history.

Through studies of rocks and fossils, geologists have produced what is called the **geologic time** scale. This is a convenient way of representing the vast amounts of time and the numerous details of historical geology in a way that is easily expressed and understood. The geologic time scale consists of the dates of major events in Earth's history, placed in chronological order. These events, primarily major extinctions and episodes of organic evolution, separate the scale into distinct time units. From largest to smallest, these units are the geologic eon, era, period, and epoch. The age of each boundary event is determined by radiometric dating of rocks associated with the time unit boundary. Radiometric dating uses the rates of atomic decay for radioactive elements to determine the age of geologic materials.

See also Big Bang theory; Dating methods; Earth science; Fossil record; Evolution, evidence of; Evolutionary mechanisms; Stratigraphy

HISTORY OF EXPLORATION I (ANCIENT AND CLASSICAL)

As early as the dawn of the world's major civilizations, people developed a long-standing curiosity about their world and universe. Exploration was a means of pushing the boundaries of known lands, as well as creating a new interpretation of the workings of the cosmos. As man wandered farther from home, he found new civilizations, wide **oceans**, and exotic goods. Growing curiosity, the desire to enhance military might, and demand for goods linked exploration and trade.

The Egyptians were the first build sea worthy ships. The earliest expedition recorded in Egyptian hieroglyphics is that of Pharaoh Snefru in about 3200 B.C. In 2750 B.C., Hannu led an expedition to explore the Arabian Peninsula and the Red Sea. After Hannu's voyage, Egyptian exploration declined until the first millennium B.C. In 550 B.C., Egyptian vessels circumnavigated **Africa**. They also constructed a canal between the Red Sea and the Nile River to facilitate trade.

The Phoenicians were perhaps the most prolific seafarers and traders of the ancient world. From their main port of Carthage, the Phoenicians dominated trade in the Mediterranean Sea. The Phoenician monopoly of trade reached from the Straits of Gibraltar to the far reaches of Persia (present-day Iran).

In 510 B.C., Greek explorer Scylax, who served in the Persian Navy, traveled to the Indus River and the mountains of present-day Afghanistan and Pakistan. He searched for new trade routes and a way to break the Phoenician trade monopoly. Pytheas sailed to the coast of modern France and established a Greek port and military garrison at Massalia (Marseilles). He then continued his expedition, later circumnavigating Britain and exploring the North Sea. The invention of a new ship, the bireme, which had two decks and four rows of oarsmen, aided the Greeks in assuming dominance over the Mediterranean.

The Roman Empire, which reached the height of its power from 100 B.C. to A.D. 400, commanded both sea and land. Sea vessels were largely used as battleships, and while the Romans did have a considerable trade fleet, the most ambitious expeditions used large war ships that carried soldiers, slaves, and plundered goods. The **area** that the Phoenicians once controlled with trade, the Romans governed over directly. The continued success of Rome depended on military conquest, territorial expansion, and the growth of the imperial economy. Rome gained dominion over lands from Northern **Europe** to Northern Africa, from Spain to Persia. They developed circular trade routes that insured that various regions of the empire received the goods and raw materials desired. Timber was exported the peripheral regions where trees were scarce. Slaves were transported to regions of production and building. Olive oil and wine was traded throughout the

Empire. These complex trade routes that insured a steady stream of raw materials and luxury goods were the model for the Atlantic triangular trade routes of the 1700s.

The European Old World was not the only venue for world exploration. In the first century A.D., Chinese explorers made rapid technological advancements, inventing the compass and complex sailing vessels, which aided open **water** exploration. Most ships had to remain in sight of land in order to navigate, but the Chinese compass, as well as Phoenician astronomical charts, permitted longer voyages, sometimes beyond the sight of land. Early Chinese sailors explored many of Asia's **rivers** and surrounding **seas**. They ventured as far as India and the eastern coast of Africa. Exploration and trade aided in the creation of a powerful and far-reaching Chinese empire.

In the South Pacific, Polynesian mariners explored the regional islands even before the recorded history. In 100-ft (30.5-m) canoes with minimal sails, Polynesians hopped from island to island, as well as made long open sea voyages. By A.D. 1000, Polynesian explorers had set foot in Hawaii and New Zealand. These Pacific sailors had a deep understanding of ocean currents and prevailing winds that was not achieved in the Atlantic until the sixteenth century.

As exploration pushed the boundaries of the known world, philosophers, astronomers, and mathematicians devised new interpretations for the workings of the world and universe. Some focused on practical challenges, such as navigation, and devised complex charts of stars. Others took a universal approach, mingling religion with exploration and science to devise of theories of how the universe and Earth itself were structured. These structures, or cosmologies, dictated the bounds of scientific reasoning and exploration. The Greek mathematician, Ptolemy, devised a model for the universe that persisted for centuries, most especially through Europe's Dark and Middle Ages (496–1450). Not until the fifteenth century and Copernican Revolution—the reemergence of concepts of a spherical Earth, and a solar system that revolves around the Sun—did scientific exploration of the earth, and beyond, reemerge.

See also History of exploration II (Age of exploration); History of exploration III (Modern era)

HISTORY OF EXPLORATION II (AGE OF EXPLORATION)

In the seventeenth century, the nature of colonialism changed. While daring expeditions at sea and discoveries of new lands still defined exploration, European nations had become dependent on the trade and resources of their New World colonies. This prompted governments to encourage settlers to move to colonial territories to establish trading ports and protect land interests. As more unknown lands were discovered, they were quickly claimed by European nations. The great territorial race began with clamoring for ownership of the vast land and resources of the New World. By the mid-eighteenth century, nations focused their attention to exploring **Africa**, the Pacific, and **Australia**. By the end of the era, European nations fought both each other and existing civilizations in the Far East for shipping and trade strongholds in **Asia**.

Colonialism and maritime discovery were not the only forces that shaped the exploration from 1600 to 1850. Knowledge gained from exploration yielded a new interest in studying the world. The Enlightenment, a resurgence in science, reason, and learning during the late eighteenth century, fostered a **climate** of scientific curiosity. Not only did people sail the **seas** to discover and claim new lands, they carefully catalogued the differing plants, animals, crops, and people in the lands they explored. New "natural sciences" such as biology and **geology** became popular pastimes for individuals. Eventually, the natural sciences gained academic credibility, by 1830, France, Spain, England, and Holland all had national geological and geographical societies.

In 1620, the Pilgrims, English settlers, landed at Plymouth, New England. While the Massachusetts Bay Colony was not the first successful settlement in the New World, it was the first major stronghold in **North America**. Soon after the English settled in Massachusetts, the Dutch sent settlers to New Amsterdam (now New York). Later in the 1600s, French Explorer La Salle claimed the northwestern coast of the **Gulf of Mexico**, naming the land Louisiana in honor of the French king. In the 1650's, the triangular trade route began. Europeans traded slaves for sugar in the West Indies, and sugar for rum, molasses, and timber in New England. This ensured a steady stream of both raw materials for industry and luxury goods for consumers.

A century later, exploration and settlement focused on Asia, the South Pacific, and Australia. In 1776, the British government proposed settlement of New South Wales, the **area** of Australia explored by **James Cook**. Two years later, the first settlers arrived in Australia. They settled around Botany Bay before relocating because of disease and poor **soil** conditions. Settlement in Australia grew quickly, especially as the French and Dutch claimed their own ports in the region, and trade in Asia flourished. The entire coastline of Australia was not fully mapped until 1822.

This mercantile economy, however, was dependent not only on colonists, but also on the procurement of African slaves. Exploration and colonialism had a devastating effect on the native populations of Africa and the Americas. Exploration and settlement brought European diseases to the populations of other continents. Virgin soil epidemics—epidemics that erupt in populations that previously had no exposure to the diseases—killed millions of people in the New World and Africa. These European diseases changed and adapted to their new climates, sometimes producing more virulent and destructive strains of disease. Thinking that certain environments caused disease, colonists became conscious of where they built their homes and towns, avoiding swamps and beaches. They often avoided fresh air and local fruits and fish, opting instead for dried beef and staples from home. Medicine during this era was closely linked to environment, a connection that sparked people's interest in the environment itself.

English explorer James Cooke embarked on perhaps the most ambitious voyage of the era in 1768. Cooke's expedition circumnavigated the globe, spending a great deal of time surveying the South Pacific and Indian **Oceans**. He discovered several island chains and surveyed a large portion of the coast of Australia. He was the first to realize that Australia was a vast continent. In 1778, Cooke voyaged to the northern Pacific in search of a passage through North America. He and his crew wintered in California, comprehensively charted the west coast of North America, and sailed as far north as Alaska and the Arctic Circle. Unable to locate an inland passage, Cooke and his crew sailed to Hawaii, which he had explored several years earlier. Cooke died in the Hawaiian Islands in 1779, but his crew returned home nearly a year later. Cooke's long expeditions fundamentally changed the shape of the known world—maps made after the Cooke voyages are some of the first to resemble modern maps.

Cooke possessed a distinct navigational advantage over his predecessors, which greatly expedited his journey and allowed for greater accuracy in mapping. In 1714, the British Parliament offered a prize to anyone who could devise a method for accurately and reliably determining longitude (position on a vertical grid of the earth). For centuries, mariners had been able to find their latitude (position on a horizontal grid of the earth), thus aiding the determination of position and distance when traveling north or south, and giving a rough position when sailing east or west. However, no means existed for accurately measuring distance and position when sailing west or east, the predominant direction of voyages to the Americas and the Far East. Most scientists thought the best way to solve the longitude problem was through the creation of astronomical charts and complex tables and equations. However, these could only be used in good **weather**, and for a few hours of the day, thus restricting their ultimate usefulness. In 1735, British inventor **John Harrison** determined that longitude is most easily calculable when one knows the exact time. On land, the most precise timekeepers were watches. Harrison thus began constructing chronometers, or clocks, for use at sea. He tested several models on various voyages, fine-tuning his models each time to account for the rocking of the ship, vibrations, and other factors that influenced the reliability of the chronometers. After nearly 30 years, Harrison perfected his chronometer in 1761. Longitudinal navigation was no longer a mystery. The British Parliament was reluctant to award the prize to an amateur scientist however, and Harrison did not receive the promised prize for several years. Realizing its potential, several navigators began to use chronometers, despite their relatively high cost, before Parliament recognized the magnitude of the discovery.

Exploration, settlement, and medicine prompted people to more closely look at nature and the environment. In 1798, Thomas Malthus published his first essay on population. The work classified peoples by region and racial characteristics, but also dealt with the relationship of each group to their environment. In the 1820s, the first rough theories of **evolution** appeared. While none deduced a specific scheme for evolving life, the concept of development began to fascinate a few people interested in the natural sciences. Along with the questioning of man's antiquity, natural scientists studied the earth itself. In 1930, the Royal Geographical Society was founded in Britain. That same year, English geologist **Charles Lyell** published his *RMS Principles of Geology*, a work that served as the standard methodology for the discipline for nearly a century. Natural scientists were fascinated with classifying all aspects of the world around them, and probing their interconnectedness. Thirty years later, a theory that proposed to explain those very connections would be the center of scientific debate in the nineteenth century. In 1831, English naturalist Charles Darwin embarked on an expedition to the Galapagos Islands, a remote island chain off the coast of present-day Ecuador. His discoveries made aboard the HMS *Beagle* foreshadowed a new age of scientific exploration, and the modern era.

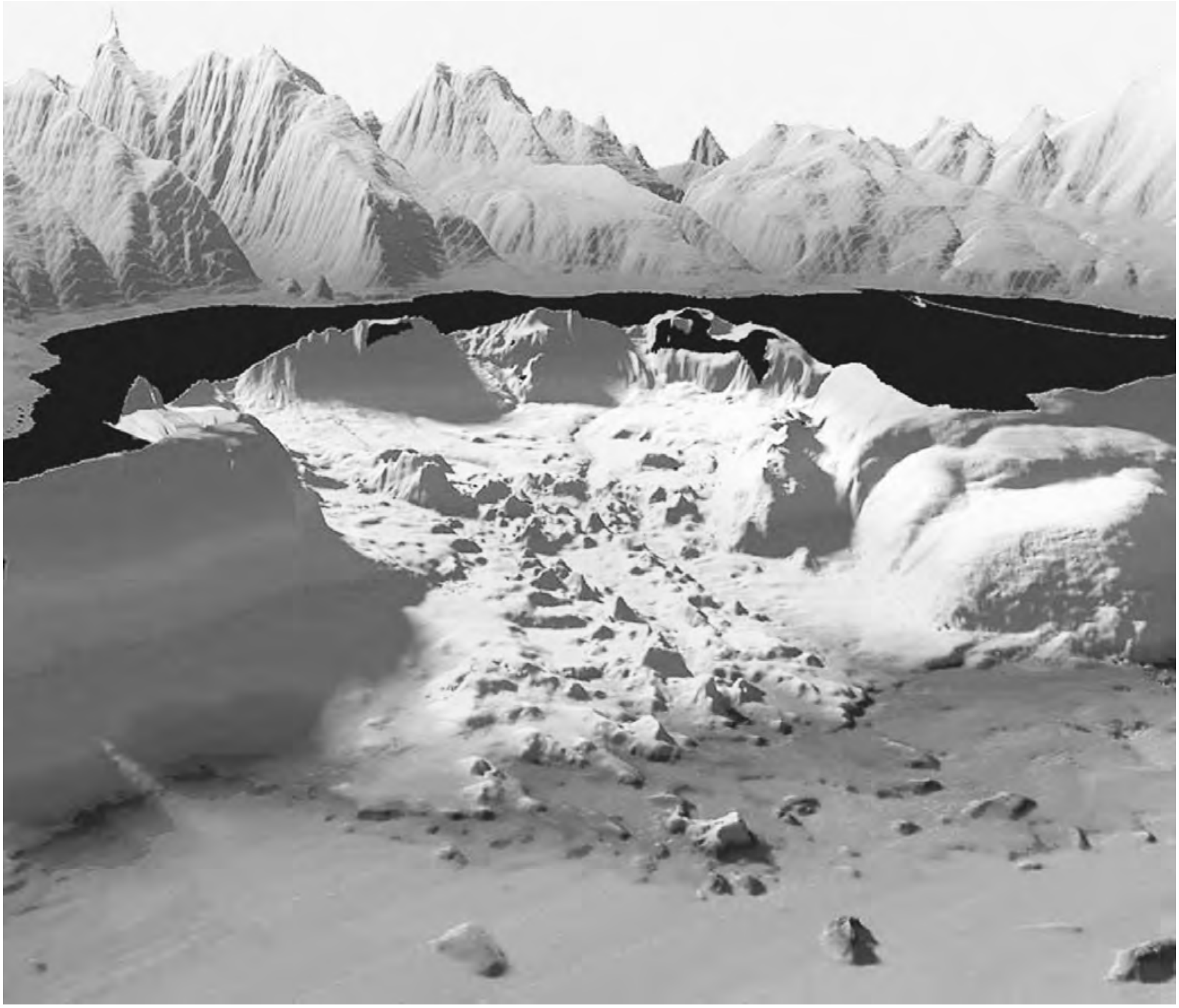
See also Cartography; Evolution, evidence of; Evolutionary mechanisms; History of exploration I (Ancient and classical); History of exploration III (Modern era); Latitude and longitude

HISTORY OF EXPLORATION III (MODERN ERA)

Until the dawn of the twentieth century, exploration of Earth's surface was limited to the surface itself. The summits of the highest mountains, the depths of the **oceans**, and sky and **space** were unexplored. Technological advances, as well as fundamental shifts in scientific theory, opened the entire world, and beyond, to exploration. The twentieth century was the golden age of discovery, rivaled only by the Copernican Revolution and the European discovery of the New World in the fifteenth century.

In 1859, Charles Darwin published a natural history work that sparked great controversy. Darwin's book, *On the Origin of Species*, was a compilation of his scientific observations from an expedition to the Galapagos Islands. Darwin's observations led him to construct a model of the **evolution** of various animal species, including man. Over the course of his career, Darwin built upon Charles Lyell's earlier works on the antiquity of Earth. Darwin proposed that the dawn of man was not because of spontaneous creation, but was the result of a process of evolution and natural selection, the principle of survival of the fittest, which occurred over hundreds of thousands of years. Darwin thus concluded that man, animals, plants, **geology**, and environment were all connected in their development. During the course of the nineteenth century, some aspects of Darwin's theory fell out of favor, such as the principles of natural selection and inheritance, after the discovery of genetics. However, Darwin's work popularized the idea of evolution, brought it into mainstream science, and opened up the fields of anthropology (the study of man) paleontology (the study of **fossils**) and geology (the study of Earth.)

At the turn of the twentieth century, wider communication was possible through the telegraph and telephone.



Modern mapping techniques allow scientists to explore Earth's least hospitable regions. Only decades ago, the bottom of Lake Tahoe was a mystery. ***AP/Wide World. Reproduced by permission.***

Railroads, steamships, and later automobiles allowed people to travel with greater ease. A voyage that took Columbus four months in 1492, took passengers a scant four days in 1915. The Panama Canal connected the Atlantic and Pacific Oceans, eliminating the need to traverse the feared and time-consuming Straits of Magellan. The advent of flight in 1901 provided the final link; within 60 years, even transatlantic passenger ships were rendered artifacts of the past. Flight also allowed man to see the surface of the earth from above, changing the way cartographers created maps. **Electricity** and cameras further revolutionized the perspectives from which people viewed the earth. This connectivity with once distant and remote places made the world seem smaller, while photography made the remote corners of the world accessible to everyone.

Exploration of the earth's surface continued. In the early decades of the twentieth century, several men led expeditions to the South Pole. In 1909, British explorer, Ernst Shackleton's voyage to **Antarctica** was particularly ill-fated, leaving much of the crew stranded on the continent as **ice** floes crushed the ship. The team did not reach magnetic south, but provided some of the first observational clues that Antarctica was a landmass, not only a **polar ice** cap like its northern counterpart. Norwegian explorer Roald Amundsen reached magnetic south in 1911, and attempted to reach the North Pole in 1926, but failed. Not until 1978 did a manned expedition reach the surface of the North Pole. In 1953, British mountaineer Sir Edmund Hillary and his guide Tenzing Norgay climbed Mt. Everest on the border between Nepal and China. The mountain is the highest peak on the earth's surface (the only larger mountains are submerged beneath the sea). Everest continues to be a draw to adventurers and explorers, claiming several lives on its harsh slopes.

By the middle of the twentieth century, most of Earth's surface had been explored. As technology grew more sophisticated and complex, explorers turned to space, the inner layers of the earth, and the unknown depths of the sea as venues for modern exploration and discovery. After World War II, the technology that was developed for the war was not only used for weapons, but also for scientific research. **Remote sensing** equipment such as sonar was used for mapping the ocean floor and locating ridges, reefs, and other underwater features. Jet engines, rockets, and robotics allowed for the launching of satellites by the United States and the Soviet Union in the late 1950s. The "Space Race" followed, with the Soviet Union and the United States each competing to achieve landmark space explorations before the other nation. In 1961, The USSR sent the first man, Yuri Gagarin, into space. The United States soon followed, sending the first astronaut to orbit Earth. Then, the ultimate goal of each nation was to send a team of astronauts to the **Moon**. In 1969, the United States sent the first team of astronauts, aboard the *Apollo 11* craft, to the surface of the moon. Aside from **meteoroids** that crashed into the earth, the Moon mission was man's first contact with an alien geology.

In the 1990s, the United States and several other nations, including Russia, renewed their interest in space research. The **International Space Station** was planned and constructed, providing the first non-earthbound research laboratory. A growing fascination with deep-space exploration and **astronomy** prompted the launch of the **Hubble Space Telescope** to photograph stellar bodies that could not be clearly investigated on the earth's surface. In 2001, missions of unmanned probes to Mars yielded information about Martian geology, giving scientists their first basis of comparison for Earth's geological processes.

Just as exploration in centuries past was largely driven not only by curiosity but also by the need for certain goods and resources, exploration in the twentieth century was similarly motivated. The Industrial Revolution created the need for vast amounts of fuels—at first **coal**, then natural gases, and then nuclear materials. The first coal mines were dug in Britain in the 1200s, and the process of mining changed little from then until the 1800s, when railroads, steam engines, and steel were introduced to expedite production, processing, and increased mine safety. Research about the deep geology of the earth's **crust** not only altered mining processes but also opened new venues to resource acquisition, such as the ocean floor, and led to the discovery of new **fuels**, such as **petroleum** and uranium. Deep-crust geology gave scientists a better understanding of how forces within the earth combine with organic materials to produce these fuels.

Today, only the uppermost layers of the planet have been explored. The technology does not currently exist to drill or explore to the molten sub-crust surfaces. While studying earthquakes and volcanoes has helped researchers understand geological processes, sub-surface exploration remains limited.

With less than ten percent of the ocean floor mapped, explored, or even seen by human eyes, the depths of the oceans are perhaps the last great arena for man's exploration of his planet. Submarines and submersibles first appeared in the 1780s, but not until the invention of the German U-boat (battle submarine) in World War I was there technology for breathing apparatuses, long-term, deep submersion, and propulsion. The first viable and practical self-contained breathing apparatus (or SCUBA) was introduced in the early 1900s. In 1930, William Beebe created a bathysphere, a personal submersible that was lowered from a ship and dragged at a given depth. Beebe dove to 1,427 ft (435 m), deeper than modern personal SCUBA equipment can attain. Beebe thus pioneered the small submersible, which later became the fixture of deep-sea exploration.

By World War II, submarines were standard naval warfare ships, and diving gear such as the Mark V diving helmet, were standard. After the war, their principals of design were applied to scientific research. In the 1970s, scientists and engineers designed a small submersible named ALVIN. The submersible had a mechanical arm, modern surveying and recording equipment, and room for up to three researchers. The submersible was motorized, and once lowered, its crew could drive it for a more free range of exploration. This generation of submersibles could be used miles beneath the surface, and entered realms of the ocean that no human had ever seen. Some of the first notable discoveries were that of deep-water marine life. Without light or heat, scientists thought that no life could survive on the sea floor. Instead, researchers discovered a vibrant community of strange and primitive-looking creatures that thrived at great depths.

In 1973 and 1974, the Mid-Atlantic Ridge, a large underwater mountain range, was explored by divers in small submersibles that were equipped with sensory and photography devices. That same decade, scientists discovered underwater volcanic vents, thus gaining insight into the creation of the ocean floor itself. The discovery of hydrothermal vents provided a new means of understanding ocean **chemistry**, and the circulation of **minerals**, necessary for sustaining marine life, at great depths. Deep-sea exploration was further utilized in archaeological endeavors to locate sunken shipwrecks and other submerged sites. In 1985, Dr. Robert Ballard, who was part of many of the great deep-ocean expeditions of the late twentieth century, discovered the wreck of the RMS *Titanic*, a British luxury liner—the technological marvel of its time—that sank in 1912.

Not all modern exploration is achieved on a grand scale. During the modern era, explorers and scientists have also embarked on projects to explore mankind, both in the past and present. Physical anthropologists unearthed early hominid (human or human-like) fossils in the African Rift Valley as early as the nineteenth century. However, not until the last half of the twentieth century did scientists attempt to establish a chronology of man to match the **desert** fossils. In 1974, anthropologists Donald Johanson and Tom Gray discovered a nearly complete hominid skeleton. The bones, named Lucy, formed the then most complete skeleton of one of the earliest known human ancestors, Australopithecus. The skeleton dates back 3.18 million years—far longer than Darwin predicted over a century before.

Today, ethnographers (people who record other cultures) and other anthropologists study groups of people around the globe, especially those who live in the most remote areas and have little contact with other peoples. Archaeologists work to unearth the material remains of the past as a means of scientifically exploring the course of human history. Thus, the exploration of man is as concerned with re-discovery as it is with novel discovery.

Marine biologists are searching for the most primitive forms of life, often small, wormlike creatures and sponges, in the depths of the ocean. Mathematician and physicist, **Albert Einstein**, paved the way for exploration of atoms, and other fundamental structures of the universe. Physicists continue to break down these elemental structures into sub-atomic particles. Other physicists and astronomers research particles, gases, and forces in space to determine provide clues about the few hundredths of a second in the life of the universe.

See also Bathymetric mapping; Dating methods; Deep sea exploration; Evolution, evidence of; Geographic and magnetic poles; Historical geology; History of exploration I (Ancient and classical); History of exploration II (Age of exploration); History of manned space exploration; Hubble Space Telescope (HST); Petroleum, history of exploration; Physical geography

HISTORY OF GEOSCIENCE: WOMEN IN THE HISTORY OF GEOSCIENCE

Women in science have been conspicuous by their apparent absence throughout history. Yet from Theano, the wife of Pythagoras, in the fifth century B.C. or Hypatia in the last days of the Roman Empire (born in A.D. 370) to **Marie Curie**, women have been practicing and teaching science and mathematics. Their profile has, however, been so low that most female scientists never made an impact on general society. From original research carried out along the western seaboard of **Europe** (United Kingdom, Ireland, France, Spain), it is clear that the population in general can only consistently cite Marie Curie as a memorable female scientist. The second most remembered female scientist is Rosalind Franklin or Dian Fosse in the English speaking countries and Hypatia (the mathematician) in France and Spain. Indeed, for nearly fifteen centuries, Hypatia was considered to be the only female scientist in history.

It is clear from the above introduction that women earth scientists were not recognized at all. Perhaps this is because it is a relatively young science; but that assumption does not stand up to scrutiny if we realize that, in what was then Germany, Agricola published his “de re Metallica,” a treatise on mining techniques, in 1556. Until recently, **geology** was divided into a practical science and a theoretical one. In addition, the amateur of the science practiced collecting for its own sake. This also applies to all the descriptive sciences. Also, it is worth noting that the prevalent view between 350 B.C. and A.D. 1600 was that science has been predominantly a male subject **area**. Most female scientists, even during the eighteenth and nineteenth centuries, were denied access to formal education and had to rely on their male relatives for tuition. With the rise of public education in America and Europe at the end of the nineteenth century, the situation did start to change. Before this, women could be considered amateur geologists in the strict sense of the word as they were rarely paid for their work. Within geology, the most popular area for female work was initially paleontology. In a paid capacity, drawing of samples or illustrating books was a favored pastime, as for example, in *Sowerby’s Mineral Conchology* in 1813.

Arguably, the first female paleontologist of note was **Etheldred Benett**, an English spinster living in the south of England. Bennett was both a scientific researcher in paleontology and an accomplished artist. The most famous early female geologist was **Mary Anning** from the United Kingdom. Sometimes called “the dinosaur woman” or the “mother of paleontology,” Anning supposedly had the tongue twister “She sells sea shells by the sea shore” made up about her. These two remarkable women were unique in that they took geological knowledge forward. However, it was not until the end of the nineteenth century that women in Europe had the chance to become professionally educated and, therefore, become professional geologists.

In America, Florence Bascom influenced female geological education significantly. She was born in 1862 in Williamstown, Massachusetts. Her mother was a suffragette, her father a professor and then president of University of Wisconsin. Her interest in geology was aroused after a visit to Mammoth **Cave**. She received degrees in 1884 and 1887, did graduate work at John Hopkins University in petrology, and was the first woman to receive a doctorate in geology in 1893. After time teaching at Ohio State University and as assistant geologist at the United States Geological Survey working on the Mid-Atlantic piedmont, Bascom subsequently founded the department of geology at Bryn Mawr College where she spent most of her adult life.

The United States Geological Survey employed their first woman geologist, Florence Bascom, in 1896, whereas the British Geological Survey did not appoint a woman until the 1920s when they were invited to apply for appointment. The female candidates were required to be unmarried or widows, and were also required to resign on marriage. Miss Eileen Guppy, the first successful woman to be employed by the British Survey, worked in the petrology department in 1927. During the Second World War, women were employed to look at water-supply boreholes and wells. The first woman was employed as a scientific officer in 1957, and the first woman to research at sea was employed in 1967.

In Canada, Alice Wilson, born in 1881 in Cobourg, Ontario, became the first woman to reach a prominent position within the Geological Survey of Canada. Her interest in Ordovician sediments and **fossils** of the Ottawa valley pushed forward geological knowledge in that country. Alice was helped in her academic pursuits by having two gifted brothers, one in geology and one in mathematics, and parents who supported education of all their children. Her father was Professor of Classics at Victoria University.

When looking at the above women it is obvious that they would not have achieved their status without determination, but also family help. That most of them were single also meant that they did not have the pressure to maintain families and children placed upon them by Victorian society or earlier prejudices, as in the case of Etheldred Benett and Mary Anning. For example, it was considered inappropriate for mothers to have careers and work outside the family sometimes even for pleasure at that time.

The early female geologists appeared to prefer paleontology. They were also single, determined, and intelligent. However, it must not be thought that the twentieth and twenty-first centuries have advanced the position of women within geology. The first fellow of the Geological Society of America was Mary Emilee Holmes in 1889. By 1930, only eleven women had been elected to fellowship of the Geological Society of America and seven of these were paleontologists. Women were only allowed into the Geological Society of London, the oldest geological society in the world, in 1919, but awards had been made to nine women prior to this date. Two late twentieth century reports from prestigious societies in Britain and the United States have highlighted the lack of equality between the genders. In 1977, a report on the status of women professional geoscientists, (something that could not have happened in the previous century) from the American Geological Institute commissioned by the Women Geoscientists Committee showed that women were moving away from the education sector toward industrial employment. However, salary inequalities still existed for more experienced women across all sectors. A report on the status of women in the Geological Society of London 20 years later in 1997 showed that women members of the society had increased to 12% (1,040) and a high percentage of these were less than 40 years old.

In United States higher education in 1977, 17% of geoscience students were female. Twenty years later in the United Kingdom, the figure had risen to 25–30%. A recent report from the Helsinki Group, a European Union research group promoting scientific research to women in general, which was reported in the journal *Science*, again emphasized the lack of women in research science. At the top of the list for female researchers is Portugal, with 48% in the natural sciences including geology. At the bottom of the list is the Netherlands with 8%. In Germany in 1994, higher education figures showed the percentage of first-year university students studying geosciences to be 30%, dropping to 15% awarded PhDs, to less than 1% for professors of geology. Women are still underrepresented in the geological world at the higher levels of expertise, but perhaps as we move through the twenty-first century, the role models from previous eras will act as an incentive for women to participate in sustaining our geological heritage.

See also Historical geology

HISTORY OF MANNED SPACE EXPLORATION

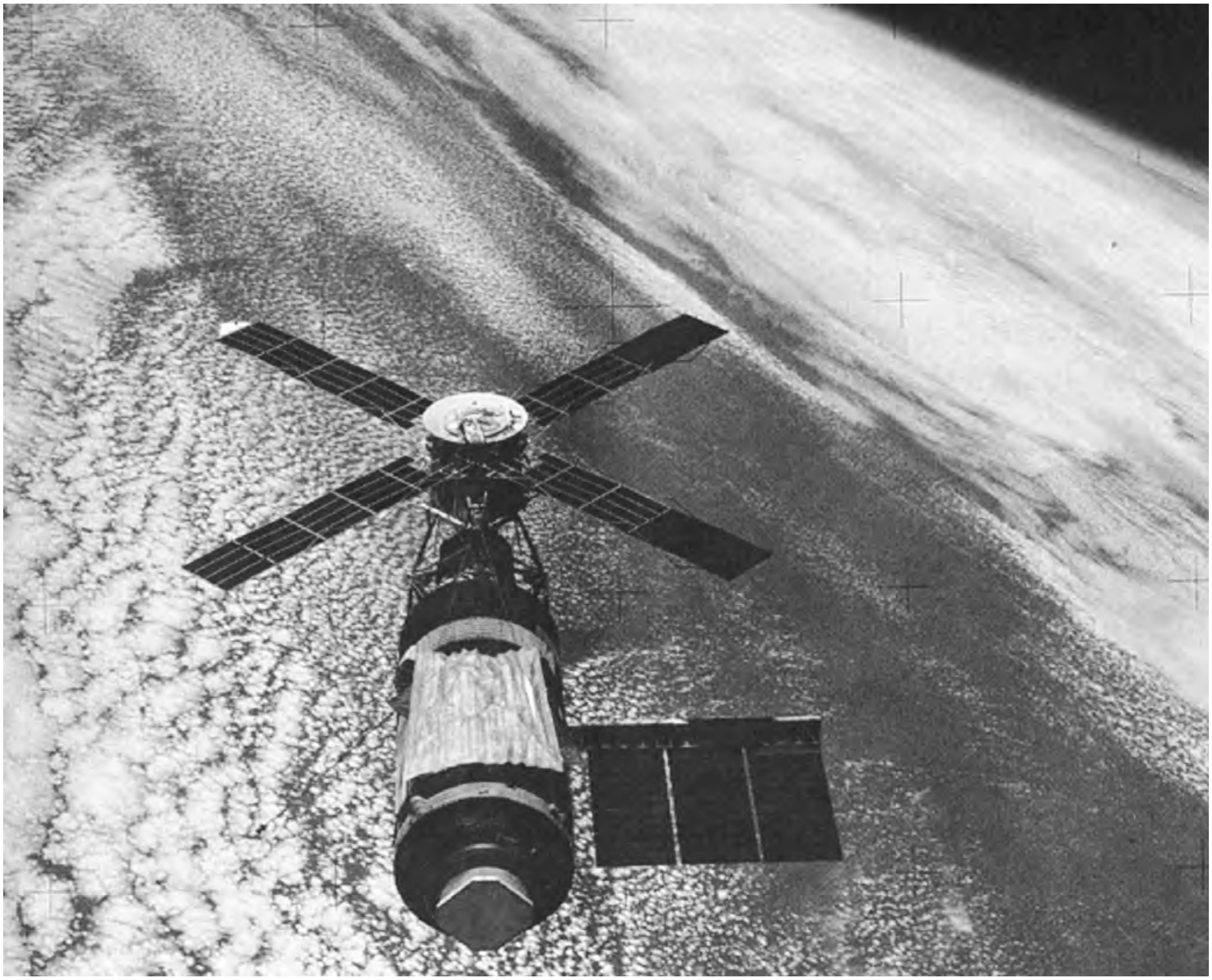
The history of manned **space** exploration is essentially the history of the United States and Soviet/Russian space programs. Although the European Space Agency and China are expected to begin manned exploration of space in the early twenty-first century—manned exploration of space in the twentieth century resulted initially from a hotly contested “space race” that was, perhaps, the most visible of Cold War competitions between the Soviet and American superpowers. Initially driven by national pride and a quest for perceived strategic military advantage, over the last two decades, the exploration of space has become a more scientifically oriented and cooperative enterprise, especially in the ongoing **joint** construction of the **International Space Station** (ISS).

The official Soviet Space Program (SSP) began in May 1946, as it was then that the government made the decision to set up an industrial branch for missile “armamentation” in the Union of Soviet Socialist Republics (USSR).

The decision to create a space program, however, was not made overnight. Since the early 1930s in the USSR, small groups of enthusiasts attempted to create rockets. These groups were made up of engineers who afterwards would play leading roles in the Soviet Space Program; among them was Soviet aeronautical engineer Sergei Pavlovich Korolev (1906–1966). A victim of Soviet purges during the late 1930s, Korolev survived a term in Stalin’s Gulag system to become the “Chief Designer” of the Soviet Space Program. Although during his lifetime Korolov’s identity was never publicly revealed to western sources, Korolev became the eventual leader of most of the SSP projects.

The success of missile building in Nazi Germany, including the creation of the V-2 rocket, influenced the beginning of rocket system development in the USSR. Immediately after the end of the World War II, a group of Soviet engineers traveled to Germany, where they carefully studied captured German documents and equipment intended for missile creation. The group even worked in Germany for a time before returning to the USSR. By 1948, the P-1 missile was already developed (the analogue of V-2) and was officially accepted as the main armament in the Soviet army. In 1950, an improved version of this missile was created, and in 1951, the new P-2 missile was first created. By 1956, the army accepted the new missile, which could carry a nuclear charge and reach its target from a distance of about 932 mi (1,500 km).

The future United States space program also received an important boost from German scientists who either fled to the United States before the war, or who intentionally fled the advancing Soviet armies to surrender to United States and British forces. Notable among these scientists was **Wernher von Braun** (1912–1977). Greatly advancing the work of early American rocket designer **Robert H. Goddard** (1882–1945), and others, von Braun would become one of the chief architects of the American Space Program and go on to design the Saturn V rocket that ultimately achieved the escape velocities needed to propel America’s Apollo program astronauts to the **Moon**.



Skylab was America's first space station. Americans have recently returned to long-term space missions with the International Space Station. ***U.S. National Aeronautics and Space Administration (NASA).***

In 1957, the two-stepped intercontinental ballistic missile P-7 was created in the USSR. Using this rocket, the world's first Earth-orbiting **satellite**, *Sputnik*, was launched on September 4, 1957 from the Baikonur cosmodrome (now in Kazakhstan). *Sputnik* weighed 187 lb (83.6 kg) and completed an elliptical orbit around the earth every 98 minutes. *Sputnik* was designed to return data about the composition and density of Earth's upper atmosphere. *Sputnik* transmitted via radio signals for approximately three weeks.

Also in the 1950s, the largest and most famous Soviet space vehicle-launching site, Baikonur, was built. This launching site is located in the Kazakhstan steppe, and the most important launches of Soviet/Russian spacecraft, in particular all spacecraft with men and women (cosmonauts) aboard, were launched from the Baikonur launch complex. Following the collapse of the USSR, the Baikonur launching site was located in an independent Kazakhstan, but Russia continues to rent and use the site for its space program.

The experimental research component of space study began under Korolev's supervision as early as 1949. Gradually, geophysics and meteorological rockets began to be launched, measurements of different geophysical field parameters at different heights were executed, and later, launching of rockets with animals on board were executed. Also in the 1950s, in parallel with military missile projects, work began on sending man into space. The result was the launch on April 12, 1961, of the spacecraft *Vostok* with the first cosmonaut, Yuri Gagarin. Aboard *Vostok,* Gagarin spent about one hour in space and completed one circuit around the earth. Shortly afterward, on August 6, 1961, the second cosmonaut, German Titov, flew to space on board the spacecraft *Vostok 2,* spending approximately one day orbiting the earth (Titov died in Moscow in 2000).

The launch of the first *Sputnik* and Gagarin's flight were triumphs of the Soviet Space Program, and the start of the unofficial space race with the Americans.

The effect on America of the spectacular early success of the Soviet Union in space exploration can rarely be overstated. Despite the design-based successes of Soviet-made MiG jet aircraft used against American forces during the Korean War, since 1947, when Charles E. "Chuck" Yeager (1923–) became the first man to break the sound barrier, America assumed it held a vast technological superiority over the Soviet Union in aeronautics and other science and engineering fields. Americans regarded the Soviet Union as nation with a struggling economy and often politically repressed scientific research programs (e.g., the debilitating effects of Lysenkoism—a Stalin-supported pseudoscientific interpretation of genetics that suppressed early Russian advances in genetics and contributed widespread Soviet agricultural shortages).

The Soviet launch of *Sputnik* and subsequently of launching the first man into orbit inflicted a deep wound to America's pride and assumed technological superiority. Near hysteria swept the American government as it feared—at a time of increasing nuclear tensions—that the demonstrated Soviet capabilities in peaceful space exploration would easily be translated into a destabilizing advantage in nuclear weapons delivery capability. Decimating the manpower and budgets of its successful high altitude aeronautics programs, the United States military and, after its founding in 1958, the National Aeronautics and Space Administration (NASA) accelerated rocket development programs. Moreover, the Soviet successes in space so rocked the American psyche that major reforms were undertaken in the educational system to close an apparent gap in scientific and engineering expertise. Education of scientists became a strategic national priority.

Although Soviet secrecy made direct comparisons difficult, the early record of the American space programs was notable for its very public failures. Rockets continually destroyed themselves in spectacular launch explosions. America's first attempted response to *Sputnik*, the Vanguard TV3 on December 6, 1957 ended in a launch failure. During 1958, four out of five intended American Pioneer probe missions (intended for lunar flybys) ended in launch failures.

Consistently behind the Soviet Union, the Americans finally successfully launched *Explorer 1* on February 1, 1958. Weeks after Gagarin's orbital flight, on May 5, 1961, the United States launched its first astronaut, **Alan B. Shepard** Jr. into a sub-orbital flight from Cape Canaveral. It was not until February 20, 1962, that astronaut John Glenn became the first American to orbit the earth. Shepard's flight so captivated and buoyed Americans, that then U.S. President John F. Kennedy issued a challenge that America would dedicate the resources needed to land a man on the Moon and return him safely before the end of the 1960s.

Before America could complete its one-man Mercury program—a series of 20 unmanned and six manned flights designed principally to test elements of rocketry and whether humans could survive and work in space—the Soviet Union increased its number of "firsts" in space exploration. One of the lone bright spots for the American space program was the success of the *Mariner 2* interplanetary probe. Launched in December 1962, *Mariner* passed within approximately 21,000 mi (33,800 km) of Venus and was able to transmit back to Earth the first useful data from an interplanetary probe.

On July 14–16, 1963, two spacecraft, *Vostok 5* and *Vostok 6*, were launched with cosmonaut V. Bykovskii on board one, and with the first woman cosmonaut **Valentina Tereshkova** on board the second. On March 18, 1965, cosmonaut Aleksei Leonov was the first to go out in open space (spacewalk) from onboard the three-man *Voskhod* spacecraft.

On June 3, 1965, American astronaut Edward H. White II became the first American to "walk in space" (i.e., perform an Extra Vehicular Activity or EVA). White's tethered EVA was part of a methodical two-man Gemini program, designed to test equipment and refine skills in maneuver and rendezvous that would be required on subsequent three-man Apollo lunar missions. Although the Soviets maintained an impressive lead in space "firsts," it was during the Gemini program—consisting of 2 unmanned and 10 manned missions—that America gained the technological ability to move into the ambitious Apollo missions.

In contrast, despite being shrouded in secrecy, by the mid-1960s, the first failures of the Soviet Space Program were apparent. First launches of Soviet N-1 rockets (the rocket intended to take Soviet cosmonauts to the Moon) were not successful, and during tests, the rocket did not reach past an altitude of 70,000 ft (21,335 m). While the "Moon race" between the United States and the USSR continued, the Soviets spent vast amounts of money (equivalent to over 600 million U.S. 1969 dollars), but when it became obvious that the USSR would not win the race—i.e., it would not be able to be the first country which would land a man on the Moon—the Moon project stagnated and the remaining N-1 rockets were dismantled.

A devastating fire during a prelaunch test on January 27, 1967, killed three *Apollo 1* astronauts and put NASA's quest to put a man on the moon by the end of the decade in jeopardy. The Soviet space program also encountered fatalities. During the first test of the *Soyuz* spacecraft in April 1967, cosmonaut V. M. Komarov was killed in a crash resulting from entangled parachute shroud lines. Another *Soyuz* accident occurred in June 1971, when a pressure leak during reentry killed all three *Soyuz* cosmonauts.

After a series of unmanned test flights, Americans returned to space on October 11, 1968, with the launch of *Apollo 7*. The success of the mission, and the stellar performance of the redesigned Apollo spacecraft put NASA on the fast track to a lunar mission. In December 1968, *Apollo 8* astronauts Frank Borman, James A. Lovell Jr., and William A. Anders became the first manned spacecraft to leave Earth orbit when they traveled to the Moon and completed 10 orbits before returning to Earth. In March 1969, the flight of *Apollo 9* remained in Earth orbit to successfully test the Lunar Excursion Module (LEM)—the first true spacecraft never designed to enter Earth's atmosphere. The 2-stage LEM was designed to carry astronauts from lunar orbit to the lunar surface and the upper stage was designed to return them to the Apollo command module that would remain in lunar orbit. In May, 1969, the flight of *Apollo 10* tested the LEM in the lunar gravitational field, as astronauts undocked the LEM from the

Apollo command module and flew within approximately 50,000 ft (15,420 m) of the lunar surface.

On July 16, 1969, the launch of *Apollo 11* propelled astronauts Neil A. Armstrong (Commander), Edwin E. “Buzz” Aldrin, Jr. (Lunar Module Pilot), and Michael Collins (Command Module Pilot) toward the Moon. On July 20, 1969, Armstrong became the first man to set foot on another world. Armstrong and Aldrin left behind an American flag and a plaque that read: “Here Men From Planet Earth First Set Foot Upon the Moon. July 1969 A.D. We Came In Peace For All Mankind.”

Having won the “space race,” the American public’s interest in lunar exploration quickly waned. Other than a renewed concern for the astronauts about the ill-fated *Apollo 13* mission, public interest and the political will to continue to shoulder the financial burdens of lunar exploration brought the Apollo program to a halt after the flight of *Apollo 17* in December, 1972.

Interestingly, it was only on the last flight of Apollo that a trained professional scientist—geologist astronaut Jack Schmitt—was able to conduct observations and conduct experiments on the lunar surface. *Apollo 17’s* emphasis on lunar **geology** and science heralded a new age of space exploration.

Also frustrating and unsuccessful for the Soviets was the Soviet **space shuttle** project, begun in 1974. In the middle of the 1980s, an experimental version of the shuttle was created, the *Buran*, but the spacecraft executed only one flight in the automatic mode (without a pilot on board) on November 15, 1988. After the collapse of the USSR, work on this project was cut because of lack of funding.

One of the most successful projects of the Soviet Space Program, however, was the creation and work of the *Mir* orbital space station. Based on extensive experience with earlier *Salyut* space stations, *Mir* became the premier Earth orbiting laboratory. The base module of *Mir*, which weighed 36 tons (32.7 metric tons), was launched on February 20, 1986. In 1987, the *Kvant* module was linked up with the station; in 1990, the *Kristall* module was also linked up with the station, and in 1990, special equipment for docking of American shuttles in the station was placed aboard *Mir*.

For several years, *Soyuz TM* spacecraft with cosmonauts on board were regularly sent to *Mir,* changing crews after periods of about 5–6 months. After launch, the spacecraft docked with the *Mir* station after traveling in space for about two days. During several missions, the crews of the spacecraft and the station conducted joint exercises, and afterwards, the old crew “passed watch” to the new one. Several days after the spacecraft’s arrival at the station, it returned to the earth with the crew who had finished the last watch.

Many scientific research projects were carried out on board *Mir*; 73 persons from nine countries visited the station and it was calculated that the total time spent onboard by all the cosmonauts was about 40 years. During 1988, cosmonauts Musa Manrov and Vladimir Titov set records for what was then the longest period of time in space for humans (366 days). Subsequently, the longest flight record was extended to 438 days by cosmonaut Vladimir Polyakov. The duration of *Mir’s* active status was much longer then expected. After ten years of utilization, different mechanical drawbacks occurred more frequently, and eventually the decision was made to end the project. The Soviet/Russian space station *Mir* was taken out of orbit and re-entered Earth’s atmosphere in 2001; its fragments sank in the Pacific Ocean.

Following the Apollo lunar program, the United States completed a more modest Skylab program. In a welcome de-escalation of Cold War tensions in 1975, the U.S. and Soviet Space programs cooperated in a joint *Apollo-Soyuz* rendezvous and docking mission. The mission was designed to pave the way for future cooperation in spaceflight.

NASA development of the Space Transportation System (STS)—the Space Shuttle—has made space more accessible to a wider variety of scientists and experts. The space shuttle has become the American workhorse for orbital delivery of wide range of satellites and repair of science instruments (e.g., the **Hubble Space Telescope**). America’s first shuttle, *Columbia,* was launched in April, 1981.

In January 1986, a disastrous explosion 73 seconds after liftoff destroyed the space shuttle *Challenger*. The explosion was due to a faulty “O” ring—a ring sealing joints in the segmented solid **rock** boosters—that was made less flexible by the cold **weather** conditions prevailing during the launch sequence. A ring failure allowed hot gasses to escape the right solid rocket booster and then to burn through to the main auxiliary fuel tank used at liftoff. The explosion claimed the life of the seven-member crew—including America’s first teacher in space, astronaut Christa McAuliffe—and halted manned U.S. space flight for more than two years.

In general, after the collapse of the USSR, the Russian space program was reduced and only recently began a revival. In spite of many different difficulties, Russia participated in the project of creating and utilizing the International Space Station. The first module (*Zarya*) of the ISS was created in Russia and launched on November 20, 1998, from Baikonur.

On December 4, 1998, the United States shuttle *Endeavor* was launched, carrying the ISS module *Unity*. American and Russian astronauts joined the two modules in open space. This event marked the beginning of the International Space Program (ISP), the official opening of which occurred on December 10, 1998. Construction of and research aboard the ISS continues.

See also History of exploration I (Ancient and classical); History of exploration II (Age of exploration); History of exploration III (Modern era); Hubble Space Telescope (HST); Space and planetary geology; Space physiology; Space probe; Spacecraft, manned

HOLMES, ARTHUR (1890-1965)

English geophysicist

Arthur Holmes, geologist and geophysicist, was born in Gateshead, England. From a modest family background, in 1907 he gained a scholarship to study **physics** at the Royal College of Science (Imperial College), London, where he became interested in the newly emerging science of **radioac-**

tivity and its application to dating **minerals** to solve geological problems.

Throughout his early life, Holmes struggled against financial hardship and frequently sought other work to support his research. Thus in 1911, he accepted a contract to prospect for minerals in Mozambique, where he conceived his vision of building a geological timescale based on radiometric dates. It was also there that he contracted a severe form of malaria.

In 1912, as a demonstrator at Imperial College, Holmes pioneered radiometric dating techniques and wrote the first of three editions of his celebrated booklet *The Age of the Earth.* In it, he estimated the earth to be 1,600 million years old, at that time an immense age and considered by many to be unacceptable. For the next 30 years, he pursued the topic, but it was not until the early 1940s that real progress was made on the geological timescale. By 1947, Holmes had pushed back the earth's age to 3,350 million years. However, it was not until 1956 that it was established at 4,550 million years.

Holmes married Maggie Howe (1885–1938) in 1914 and his first son was born in 1918. He escaped active service in the First World War due to recurring bouts of malaria but, by 1920, he was still only earning 200 pounds a year. Once again financial necessity compelled him to accept a post abroad, this time in Burma as chief geologist to the Yomah Oil Company (1920) Ltd. By 1922, however, the company had collapsed. Six weeks before leaving for home his young son caught dysentery and died. Eighteen months of unemployment followed Holmes' return to England, during which time he opened a Far Eastern craft shop in Newcastle-upon-Tyne.

In 1924, Holmes was offered the headship of a one-man **geology** department at Durham University. With his fortunes revived, and enhanced by the birth of his second son, this period saw an invigorated renewal of his research activities. An immediate supporter of the **continental drift theory**, originally proposed by Wegener in 1912, Holmes saw at once that it explained how identical **fossils** and **rock** formations occurred on either side of the Atlantic. However, the theory was then highly controversial, as no force was considered adequate to move continental slabs over the surface of the globe. It was Holmes' profound understanding of radioactivity—the amount of heat it generated and the enormous time it bestowed on geology for infinitely slow processes—that placed him in a unique position to formulate such a mechanism.

In 1927, Holmes gave a seminal paper which proposed that differential heating of the earth's interior, generated by the decay of radioactive elements, caused convection of the substratum (mantle). He calculated that convection could produce a force sufficient to drag continents apart, allowing the substratum to rise up and form new ocean floor. Evidence to corroborate this theory was not found until 1965, the year of Holmes' death, but by then his ideas were largely forgotten.

During the Second World War, Holmes was commissioned to write *Principles of Physical Geology.* Published in 1944, this famous book with its heretical chapter on continental drift, became an international best-seller that influenced generations of geologists. When Holmes retired in 1956, he set out to update the book, but with failing health it was a mammoth task, completed only months before he died.

Recognition of Holmes' outstanding contributions to geology came when he was elected Fellow of the Royal Society in 1942 and a year later appointed to the Regius chair in geology at Edinburgh University. In 1956, the Geological Societies of London and America awarded him their highest honors. In 1964, he was presented with the Vetlesen Prize, the geologist's equivalent of the Nobel Prize, for his "uniquely distinguished achievement in the sciences resulting in a clearer understanding of the earth, its history, and its relation to the universe."

Holmes was a deep thinker on the broad philosophical aspects of geology, with ideas far ahead of his time. Always of smart appearance, he was a gentleman of quiet charm and unfailing kindness. He had an exceptional talent for playing the piano, was fascinated by history, and loved poetry. In 1931, Holmes met Doris Reynolds (1899–1985), a geologist then working at University College, London. He engineered a lectureship for her in the Durham geology department, but they were unable to marry until 1939, nine months after the death of his first wife from cancer. Holmes died of bronchial pneumonia in 1965, leaving his beloved Doris to succeed him by 20 years.

See also Dating methods; Geologic time

HOLOCENE EPOCH

Earth is currently in the Holocene Epoch. In **geologic time**, the Holocene Epoch represents the second epoch in the current **Quaternary Period** (also termed the Anthropogene Period) of the current **Cenozoic Era** of the ongoing **Phanerozoic Eon.** The Holocene Epoch ranges from approximately 10,000 years ago until present day.

Also termed the Recent Epoch, the Holocene Epoch is thus far notable for the retreat of glaciers—a major force in producing the landscape topographical features evident today—and the geological time during which humans (*Homo sapiens*) became the dominant life form on Earth, increased their societal relationships, and produced major civilizations. The retreat of **glaciers** and the gradual climactic warming in the Northern Hemisphere encouraged migration and biological radiation of species.

Although *Homo sapiens* appeared during the preceding **Pleistocene Epoch**, and were fully differentiated as a species by the beginning of the Holocene Epoch, human societal **evolution** has taken place during the Holocene Epoch. As expected, the most recent and superficial of sedimentary remains were laid down during the Holocene Epoch. The **fossil record** is also dotted with an archaeological record of human activity and civilization.

Human societal and intellectual development during the Holocene Epoch produced the first species capable of significantly and consciously altering geophysical processes. In addition to deliberate reworking of topographical features and use of natural resources, byproducts of human civilization and industrialization have affected **groundwater** reservoirs, the type of abundance of **weathering** agents, the **geochemistry** of atmospheric processes on a local scale (e.g., **acid rain**); and possible atmospheric and/or marine processes on a global scale (e.g., possible **global warming**).

The general retreat of **glaciation** was punctuated by smaller-scale "ice ages"—including the "Little **Ice** Age" that occurred between approximately 1150 and 1700. One of the reasons that it is difficult for modern scientists to quantify the possible extent in global warming is that accurate climatic data extends back, at best, only about a hundred years. Accordingly, it is difficult to determine whether any data indicating global warming is simply a normal variation in a general downtrend, or a normal variation in generalized warming pattern.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Pliocene Epoch; Precambrian; Proterozoic Era; Silurian Period; Supercontinents; Tertiary Period; Triassic Period

HORNFELS

Hornfels is a fine-textured **metamorphic rock** formed by contact **metamorphism**. Contact metamorphism occurs when a mass of hot **magma** intrudes into preexisting **rock**, whether by injecting itself into a crack or by ascending in a large body (e.g., **pluton**). Rock in close proximity to the magma is temporarily softened or melted and recrystallizes with an altered texture, producing a hornfels. The term hornfels is often restricted to rocks produced by contact metamorphism of shale, **slate**, or mudstone.

In contrast to schists and gneisses, hornfelses show little or no foliation or layering. They form under conditions of approximately anisotropic (directionless) stress, so there is no tendency for the **crystals** to align in any particular direction. Traces of **bedding** present in the parent rock may remain in a hornfels but are not caused by metamorphosis.

Because they form by contact metamorphosis, hornfelses occur in shells or layers around bodies of intrusive magmatic rock. When seen in cross-section, as at Earth's surface, these shells or layers appear as rings or bands surrounding areas of magmatic rock. These rings are termed contact aureoles. A contact aureole may be only a few centimeters thick or several kilometers thick, depending on the size of the magmatic intrusion. An aureole of less-metamorphosed rocks, often spotted slates and semihornfels, frequently surrounds the hornfels aureole and blends smoothly with it. As is generally the rule with metamorphic rocks, coarser texture in a hornfels indicates more thorough **melting** and slower recrystallization.

Hornfels may be chemically altered by the magma that metamorphoses them, but generally reflect the chemical composition of their parent rocks; thus, **quartz**, **feldspar**, biotite, muscovite, pyroxenes, garnet, and calcite are common ingredients of hornfelses. However, as hornfelses are defined by process of origin (contact metamorphism), not by composition, one must establish that a rock has originated in a contact aureole to classify it as a hornfels.

See also Country rock; Intrusive cooling; Metamorphic rock

HOTSPOTS

Hotspots are localized areas of volcanism and high heat flow within the earth's **lithosphere** above a mantle plume hot enough to melt portions of the overriding plate. As a plate moves over a mantle plume, volcanoes previously above the plume cease to be active and new volcanoes form, creating an arcuate chain of volcanoes whose ages change progressively along the chain. The approximately 3,790 mi (6,100 km) long chain of Hawaiian volcanic islands and Emperor seamounts (submarine volcanoes) were formed by the displacement of the Pacific plate over a mantle plume. The age of volcanoes, degree of **erosion**, and general maturity of the Hawaiian Islands decreases progressively southeastward. The volcanically active Big Island overlies the present-day hotspot. The chain of volcanoes decreasing in age from west to east across the western United States and ending at Yellowstone National Park formed by the North American plate moving westward over the Yellowstone plume. Iceland lies above a hotspot at a mid-oceanic ridge.

Hotspots were thought to remain in a fixed position with respect to the earth's lower mantle. Hotspots were therefore used to define a unique, absolute reference frame to quantify the displacement of **lithospheric plates**. Maps of absolute velocity vectors for the earth's plates relative to hotspots (first produced in the late 1970s) provide a visual representation of plate motion from which the sense of displacement and resulting style of deformation at plate margins can be deduced. Hotspot tracks define segments of small circles about a fixed pole of **rotation** for the plate (called the Euler pole). Paleomagnetic studies of volcanic rocks formed above hotspots and detailed global plate reconstructions suggest that at least some hotspots may not have remained stationary. Rates of relative hotspot movement have been generally estimated at approximately 0.8–1.2 in (20–30 mm) per year. This implies that plumes may have moved with part of the mantle and displaced relative to each other. If the density distribution of the mantle changed in the past, the whole mantle may have rotated with respect to the earth's rotational axis to a new stable position (a process called true polar wander), systematically rotating all hotspots relative to the rotational axis. Paleomagnetic studies of volcanoes along hot-spot tracks are used to determine if true polar wander is likely to have occurred in the period of time recorded by the volcanoes.

See also Hawaiian Island formation; Paleomagnetics

HOWARD, LUKE (1772-1864)

English pharmacist and meteorologist

Luke Howard classified and named cloud formations. He understood that even though **clouds** have a countless variety of shapes, they have only three basic forms, which he termed cirrus (hair curl), cumulus (heap), and stratus (layer). There can be combinations of any of these three, such as cumulostratus or cirrocumulus. Any of them can also be a "nimbus" (rain) cloud, such as cumulonimbus. High clouds are designated by the prefix "alto-," such as altostratus.

Howard was born in London, England, on November 28, 1772, the eldest son of a prosperous businessman, Robert Howard, and his wife Elizabeth, née Leatham. As devout Quakers, the family enrolled Luke in a prominent Quaker institution, Thomas Huntly's School in Burford, near Oxford, from 1780 to 1787. That was the extent of his formal education. Although not trained as a scientist, he learned enough **chemistry** and pharmacy on his own to become a successful manufacturer, wholesaler, and retailer of pharmaceutical preparations. He began his business in London in 1793, partnered with William Allen in London and Plaistow, Essex, from 1796 until Allen's death in 1803, moved the business to Stratford while continuing to live in Plaistow, and eventually became head of the firm Howards and Sons. Throughout his life he supported himself with this trade.

Howard was fully dedicated to four main concerns: his business, his religion, his family, and his hobby, **meteorology**. On December 7, 1796, he married Mariabella Eliot, who shared his amateur interest in meteorology, helped him to gather data, and encouraged him to disseminate his findings. From an early age he loved clouds, and would spend hours watching them or painting watercolors of them. Gradually his observations and experiments, mostly conducted at home in his garden, became more precise and systematic.

Before Howard's time there was no useful classification of clouds. They were described haphazardly in terms of their color, size, shape, density, persistence, altitude, and moisture content. The eighteenth-century enthusiasm for classifying everything imaginable had not succeeded with clouds, even though scientists as reputable as Jean Baptiste Lamarck (1744–1829) had worked on the problem. Howard solved it with a simple threefold schema, which he presented in a famous lecture to the Askesian Society in London in 1802. This talk was published as "On the Modifications of Clouds" in 1803. Overnight Howard was a sensation. Within a decade, his classification was in general use throughout Western **Europe**. Not only scientists, but also poets such as Percy Bysshe Shelley (1792–1822) and Johann Wolfgang von Goethe (1749–1832) and painters such as Joseph Mallord William Turner (1775–1851) and John Constable (1776–1837) praised him for his meteorological breakthrough and its contribution to their professions.

Besides his work on clouds, Howard published articles and essays on pollen, **atmospheric pressure**, meteorological instrumentation, the **seasons**, **precipitation**, **electricity**, and **evaporation**, plus a three-volume book called *The Climate of London*, as well as anti-slavery pamphlets and several apologies for Quakerism. For his contributions to meteorology and climatology, he was elected a Fellow of the Royal Society in 1821.

Howard moved from Plaistow to Tottenham, near London, in 1812 and to Ackworth, Yorkshire, in the mid-1820s. After Mariabella died in 1852, he moved in with his son, Robert, at Bruce Grove, Tottenham, where he died on March 21, 1864.

See also Clouds and cloud types; Meteorology

HOYLE, FRED (1915-1999)

English astronomer

A prolific and talented author in both science fact and fiction, Fred Hoyle is best known for publicizing the controversial steady state theory of the creation of the universe. Hoyle also helped develop radar and advance the understanding of the nuclear processes that power the stars. He has taught at both Cambridge and Cornell universities, received numerous awards and honors, and was knighted in 1972.

Born in Bingley, Yorkshire, England, Hoyle was the son of Benjamin Hoyle and Mabel (Picard) Hoyle. He attended Bingley Grammar School and went on to Emmanuel College at Cambridge, where he studied mathematics and **astronomy**, receiving his master of arts degree in 1939. On December 28, 1939, Hoyle married Barbara Clark and the couple eventually had two children.

During World War II, Hoyle served in the Admiralty at London, where he helped the British Navy develop radar (radio detection and ranging) technology. The Royal Air Force's victory in the Battle of Britain has been credited to the navy's improvement of radar during this period. After the war, numerous radar dishes were acquired by fledgling radio astronomers and converted into radio telescopes. These amateurs' discoveries in the 1960s ultimately helped to refute the theories Hoyle developed in the 1940s and 1950s.

During the early 1940s, Hoyle focused his attention on an issue that arose through the work of physicist Hans Bethe: energy production in stars. In 1938, Bethe had suggested a sequence of nuclear reactions that fuel the stars: Four hydrogen atoms were fused into a single **atom** of helium, resulting in a minute amount of mass being converted into energy. While this process of **nuclear fusion** was consistent with the predicted amounts of stellar energy observed, Bethe's theory did not account for the production of elements heavier than helium—heavy elements that exist within other stars and that are also abundant on Earth.

Hoyle expanded Bethe's findings. Elaborating on gravitational, electrical and nuclear fields, he determined what would happen to elements at ever increasing temperatures. He theorized that when a star has nearly exhausted its supply of hydrogen, nuclear fusion halts, and the outward radiation pressure generated by the fusion reaction also comes to a halt. Without this outward flow, the star begins to collapse because of gravitation. This causes the core of the star to heat up and reach a **temperature** great enough to fuse helium into **carbon**.

The collapse of the star is then halted by the outward pressure of this new fusion radiation, and the star becomes stable. Hoyle's investigation into the nature of the carbon atom had the added benefit of helping scientists understand the origin of the atoms within the human body.

As the fusion cycle of **stellar evolution** continues, **oxygen**, magnesium, sulfur and heavier elements build up until the element **iron** is formed. At this point, no more fusion reactions can occur, and the star collapses catastrophically, becoming a white dwarf (a star dimmer than the **Sun** but much more dense). During this implosion, the star's outer layers ignite to become a supernova (an explosion whose luminosity is many times greater than the Sun). The supernova explosion creates elements heavier than iron, which are then hurtled into **space** by the explosion's force. It was from stellar debris such as this, Hoyle hypothesized, that the second generation stars with the heavier elements were formed.

Hoyle further proposed that the Sun was once part of a binary (double) star system whose companion became a supernova eons ago. The resulting heavy elements it ejected into space became the material from which the planets were formed. Hoyle's remarkable theory of stellar **evolution** appeared to be correct; it agreed with scientists' observations and accounts for the heavy elements in the **solar system**. However, whether the Sun had a companion star or not is still disputed; some believe a passing star was the culprit.

Following the war, Hoyle returned to Cambridge and became a professor of astronomy and mathematics. The pivotal point in his career came in 1948 when nuclear physicist George Gamow, building upon a theory first suggested by Georges Lemaître, a Jesuit priest and astonomer, and supported by the telescopic observations of the astronomer Edwin Powell Hubble, published what became known as the **big bang theory** of the creation of the universe. The big bang theory states that billions of years ago there was an enormous explosion in which all the matter of the universe was created. Galaxies formed and evolved from this matter and are still moving away from each other at tremendous velocities as a result of the explosion.

The concept that the universe had a specific beginning—and the implication that it will have an end—was abhorred by many scientists and laymen. Consequently, Thomas Gold and Hermann Bondi, an astronomer and mathematician respectively, proposed the steady state theory that theorized that the universe was perpetual, an idea that appeared to agree with scientific observation. Through the steady state theory, Gold and Bondi conceived of a universe in which matter was created continuously. As galaxies drift apart, new matter appears in the void and evolves into new galaxies. Since the universe seemed homogeneous (the same) regardless from which direction it was observed, or how far away (i.e. how far back in time) it was observed, Gold and Bondi suggested the cosmos was the same every "where" and every "when." That is, the physical state of the universe remains the same in the past, the present, and the future. The steady state concept had several virtues, not the least of which was avoiding the troublesome issue of the beginning and end of creation. It was simple, symmetrical, and attracted as many adherents as did Gamow's big bang theory. Hoyle became one of steady state's most influential and talented supporters.

Gold and Bondi had not based their concept on general field theory, but instead on an intuitive physical principle. To rectify this, Hoyle delved into the complex equations of **Albert Einstein**, modified them, and produced a mathematical model that supported the steady state theory, thereby giving it both respectability and plausibility. He became the official spokesperson for the theory and produced many books, some extremely technical, others geared for popular consumption, that publicized steady state **cosmology**.

The greatest objection to the steady state theory concerned the issue of the continual creation of new matter forming from nothing—an idea that seemed to violate the laws of nature. Hoyle claimed it was easier to accept the idea of matter being created slowly and continuously over the eons than believing that all matter in the universe was created in a single instant from a single blast. For the next fifteen years, proponents of each side interpreted new astronomical discoveries in ways that supported the theory to which each adhered.

In 1952, however, astronomer Walter Baade demonstrated that the accepted cosmological "yardstick" of measurement was seriously flawed. This "yardstick" was derived from the relationship between the brightness and the rate of pulsation of certain stars called Cepheid variable stars. According to Baade's findings, such stars were much farther away than had been previously calculated. This meant that the universe was much older, had been evolving longer, and was more than two times larger than had been believed. If the steady state theory were to hold up, astronomers surveying space would expect to see "old" galaxies created billions of years ago and containing aging stars, as well as "new," recently-created galaxies containing lighter elements and new stars. Yet observed galaxies appeared to be similar in age, supporting the big bang theory. Proving that matter is continuously created was more complicated than it seemed for the steady state theorists. Since space is so vast and the amount of matter that needs to be created at a given moment for the theory to be proven was so small, scientists were not able to detect the instantaneous creation of matter.

The debate between the factions continued. Hoyle acknowledged in his 1962 book *Astronomy* that there are "cosmological theories in which the universe had a finite and 'explosive' origin," but he manages to discuss them without once using the contentious phrase "big bang"; an ironic point since the term "big bang" is attributed to Hoyle. A decade earlier, Gamow's book *The Creation of the Universe* remarked that "Astronomical observations" concerning the brightness of the Milky Way stars in relation to the brightness of neighboring stars suggest "that the theory of [Bondi, Gold, and Hoyle] may not correspond to reality." In order to maintain the relevance of his work, Hoyle made several modifications to the steady state theory throughout the 1950s and 1960s.

The 1963 discovery of **quasars** by Maartin Schmidt created an awkward complication for the steady state theory.

Quasars, distant objects brighter than and emitting more energy than stars, did not fit into the steady state explanation of the universe. This tipped the balance toward the big bang theory, which had no trouble embracing these "quasi-stellar" objects. In the following year, **Arno Penzias** and **Robert W. Wilson** discovered background microwave radiation in outer space by using radio telescopes. Claiming they had discovered the "remnants" of the big bang explosion with their telescopes, which had evolved from Hoyle's work on radar during World War II, Penzias and Wilson sealed the fate of the steady state theory, which was now abandoned in favor of the big bang theory. Subsequently, Hoyle found working with radio astronomers at Cambridge University increasingly difficult. When his proposed grant for a computer was rejected by the Science Research Council in 1972, Hoyle left the university in favor of working elsewhere.

Hoyle stirred up controversy again in 1981, when he proposed that one-celled life could be found in interstellar dust or **comets** and life on Earth may have originated from a close encounter with a comet. He also suggested that the abrupt appearance of global epidemics could be caused by space-borne contaminants, a suggestion not taken seriously by most scientists. In 1985, Hoyle ignited yet another controversy when he claimed that the British Museum's fossil of Archaeopteryx was a fake, but he had not been alone in that contention.

A prodigious amount of information has flowed from Hoyle's pen during his career. With his talent for simplifying complex theories for general audiences, he has produced technical treatises, textbooks, popular science fiction stories, an opera libretto, even a radio and a television play. The radio play, *Rockets in Ursa Major*, and the television play, *A for Andromeda*, were both written in collaboration with his son, Geoffrey, in 1962. His research on the development of stars and their age, including giants and white dwarfs, helped establish some of cosmology's major theories.

During his career, Hoyle was widely recognized for his achievements with many honors. In 1956, he became a member of the staff at Mount Wilson and Palomar observatories. In 1957, he was elected to the Royal Society of London; the following year he became Plumian Professor of Astronomy and Experimental Philosophy at Cambridge, and in 1962, he became the director of the Institute of Theoretical Astronomy. Following his departure from Cambridge in 1972, he became professor-at-large at Cornell University. Hoyle died at the age of 86.

See also Stellar life cycle

HUBBLE, EDWIN (1889-1953)

American astronomer

Edwin Hubble was an American astronomer whose impact on science has been compared to pioneering scientists such as the English physicist Isaac Newton and the Italian astronomer Galileo. Hubble helped to change perceptions of the universe in two very important ways. In an era when the Milky Way was perceived as the extent of the entire Universe, Hubble confirmed the existence of other galaxies through his observations from the Mount Wilson Observatory in Pasadena, California. Furthermore, with the help of other astronomers of his time, Hubble showed that this newly discovered Universe was expanding, and developed a mathematical concept to quantify this expansion now known as Hubble's law.

Edwin Powell Hubble was born in Marshfield, Missouri to John P. Hubble, an agent in a fire insurance firm, and Virginia Lee James Hubble, a descendant of the American colonist Miles Standish. The third of seven children, Hubble spent his early childhood in Missouri, entering grade school in 1895. In 1898, John Hubble transferred to the Chicago office of his firm, and the Hubble family moved first to Evanston and then to Wheaton, both Chicago suburbs.

Hubble attended Wheaton High School, excelling in both sports and academics. He graduated in 1906 at the age of sixteen, two years earlier than most students. For his efforts, he received an academic scholarship to the University of Chicago, where he studied mathematics, **physics**, **chemistry**, and **astronomy**. In the summer, Hubble tutored and worked to earn money for his college expenses. In his junior year he received a scholarship in physics, and by his senior year he was working as a laboratory assistant to physicist Robert A. Millikan. Hubble graduated in 1910 with a B.S. in mathematics and astronomy. In addition to his academic career, the six-foot-two-inch Hubble was an amateur heavyweight boxer.

In 1910, Hubble was awarded a Rhodes Scholarship, following which he went to attend Queen's College at the University of Oxford in England. There he studied jurisprudence, completing the two-year course in 1912. He began working on a bachelor's degree in law during his third year, but renounced it for Spanish instead. He also continued his athletic endeavors, excelling in the high jump, broad jump, shot put, and running. In 1913, Hubble returned to the United States and began practicing law in Louisville, Kentucky, where his family was now living. Bored with his law career within a year, Hubble returned to the University of Chicago in 1914 to work towards his doctorate in astronomy.

At the time Hubble attended the University of Chicago, Yerkes was a waning institution that did not actually offer formal courses in astronomy. However, working under the supervision of Edwin B. Frost, the observatory's director, Hubble made regular observations on Yerkes' **telescope** and studied on his own. It is believed that Hubble's work at this time was influenced by a lecture he attended at Northwestern University. At the presentation, Lowell Observatory astronomer, Vesto M. Slipher presented evidence that spiral nebulae (in that era, the term nebulae was used to describe anything not obviously identifiable as a star) had high radial velocities—the velocities with which objects appear to be moving toward or away from us in the direct line of sight. Slipher found spiral nebulae that were moving at much higher velocities than stars generally moved—evidence that the nebulae might not be part of the Milky Way.

During his term at Yerkes, Hubble also met astronomer George Ellery Hale, founder of the Yerkes Observatory and then the director of the Mount Wilson Observatory in Pasadena, California. Hale had heard of Hubble, and in 1916, invited him to join the Mount Wilson Staff once he received his doctorate. However, Hubble's acceptance of this offer was delayed by World War I, which he joined in 1917. Hubble attained the rank of major, and after his discharge in 1919, he finally began work at Mount Wilson. The observatory had two telescopes, a 60–in (152–cm) reflector and a newly operational 100–in (254–cm) telescope, the largest in the world at that time. It was here that Hubble began the major portion of his life's work.

Hubble's first notable achievement at Mount Wilson was the confirmation of the existence of galaxies outside the Milky Way. From observations made in October 1923, Hubble was able to identify a type of variable star known as a Cepheid in the Andromeda nebula (known today as the Andromeda galaxy). By using information about the relationship between brightness, luminosity (how much light a star radiates) and the distances of Cepheid stars in our galaxy, Hubble was able to estimate the distance to the Cepheid in the Andromeda nebula to be about one million light years. Hubble also discovered other Cepheids, as well as other objects, and calculated the distances to them. Since scientists knew that the maximum diameter of the Milky Way was only 100,000 light years, Hubble's figures established the existence of galaxies outside our own. Eventually, he determined the distances to nine galaxies. Consistent with scientific terminology of his time, Hubble called these "extragalactic nebulae." The results of Hubble's work were publicly announced at the December 1924 meeting of the American Astronomical Society, settling one of the great scientific debates of that era.

Also in 1924, Hubble married Grace Burke Leib. His personal interests included dry-fly fishing (his favorite fishing haunts were in the Rocky Mountains and in England) and collecting antique books about the history of science. He served as a member of the Board of Trustees of the Huntington Library in San Marino, California from 1938 until he died in 1953.

Hubble's work at Mount Wilson was interrupted during World War II, when he served as chief of exterior ballistics and director of the supersonic **wind** tunnel at the Ballistics Research Laboratory at Aberdeen Proving Ground in Maryland. He worked at Aberdeen from 1942 to 1946 and received a Medal of Merit for his efforts.

Returning to Mount Wilson after the war, Hubble continued his observations of galaxies. In 1925 he introduced a system for classifying them at a meeting of the International Astronomical Union; according to this system, galaxies were either "regular'' or "irregular." In addition, regular galaxies were either spiral or elliptical, and each of these classes could be further subdivided. The system used to classify galaxies today is still based on Hubble's structure.

In 1927 Hubble was elected a member of the National Academy of Sciences, but another great achievement was yet to come. By combining his own work on the distances of galaxies with the work of American astronomers Vesto M. Slipher and Milton L. Humason, Hubble proposed a relationship between the high radial velocities of galaxies and distance. He systematically looked at a number of galaxies and found that except for a few nearby, all of the others were moving away from us at high speed. He discovered a **correlation** between this velocity and distance, and the result was a mathematical concept now known as Hubble's law. Simply put, Hubble's law states that the more distant a galaxy is from us, the faster it's moving away from us. Although Hubble didn't actually discover that the universe is expanding, he put the theory together in a coherent way. Today, the expanding universe is part of the big-bang theory of the creation of the universe.

HUBBLE SPACE TELESCOPE (HST)

The Hubble Space **Telescope** (HST) is a large Earth-orbiting astronomical telescope designed by the United States National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Hubble observes the heavens from 380 mi (612 km) above the earth, relaying pictures and data captured above the distortions of Earth's atmosphere. The HST is named after American astronomer Edwin P. Hubble (1889-1953), who early in the twentieth century provided evidence of an expanding universe consisting of many galaxies beyond our Milky Way galaxy. The HST has provided scientists with the clearest views yet obtained of the universe. Moreover, stunning images and spectrographic data sent from the HST provide scientists with critical data relevant to studies regarding the birth of galaxies, the existence of black holes, and the workings of planetary systems around stars.

Deployed from the **space shuttle** *Discovery* on April 25, 1990, the Hubble Space Telescope was the culmination of a 20-year scientific effort to construct one of the largest and most complex satellites ever built. Astronomers first proposed the idea of building an orbiting observatory in the 1940s. The $1.5 billion project to build the Hubble Space Telescope began in earnest in 1977 after the United States Congress passed a resolution granting approval for the HST construction. By 1985, the HST was completed and ready for launch. The explosion of the space shuttle *Challenger* and loss of its crew in January 1986 delayed the Hubble's launch four years. As NASA officials re-evaluated the space shuttle program, the HST was relegated to storage—at a maintenance cost of up to one million dollars a month.

The HST is roughly the size of a school bus, and is modular in design to facilitate in-orbit servicing. Like any reflecting telescope, the Hubble uses a system of mirrors to magnify and focus light. The primary mirror is concave, and a smaller convex secondary mirror is placed in front of the primary mirror to boost the telescope's total effective focal length. The telescope receives its main power from a pair of flexible, lightweight solar arrays. Each array is a large (40 ft by 8 ft, or 12.2 m by 2.4 m) rectangle of light-collecting solar cells. Exterior thermal blanketing protects the HST from the extreme **temperature** changes encountered during each 95-minute orbit of the earth.

Shortly after the 1990 launch of the HST, scientists found the telescope was unable to adequately focus light to provide desired resolutions. Fuzzy halos appeared around objects observed by the HST. The culprit was found to be a defect in the primary mirror. As a result of an incorrect adjustment to a testing device, the mirror was precisely, but inaccurately, ground to a curvature that was too flat at its edge. Although the error measured less than a micron (one ten-thousandth of an inch), the defect caused a spherical aberration when light reflected by the mirror focused across a wider **area** than necessary for a sharp image. The problem was corrected in December 1993 when, following an orbital rendezvous between the space shuttle *Endeavor* and the HST, the crew of *Endeavor* completed the first Hubble servicing mission. During the eleven-day operation, the Corrective Optics Space Telescope Axial Replacement (COSTAR) was installed. COSTAR corrected the spherical aberration of the HST primary mirror with a series of mirrors designed to act as corrective "eyeglasses" able to focus the blurred uncorrected image.

The Hubble Space Telescope carries a variety of on-board, scientific instruments designed to collect and send data to awaiting scientists. As needed, instruments are replaced or added during Hubble servicing missions. In 1977, two spectrographs were replaced with the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS), and the Space Telescope Imaging Spectrograph (STIS). NICMOS allows the telescope to see objects in near-infrared wavelengths. These observations are important in **astronomy**, as well as in the study of the visible-light-obscuring gas and dust nebular clouds where stars are born. The STIS collects light from hundreds of points across a target and spreads it out into a spectrum, creating an image from which scientists can study individual wavelengths of radiation from a distant source. STIS is especially helpful to scientists studying regions of space where black holes are presumed to exist. In 1993, the HST's original Wide Field Planetary Camera was replaced with an updated version complete with relay mirrors spherically aberrated to correct for the spherical aberration on the Hubble's primary mirror. In 1999, the HST received a new high-speed computer.

Once the Hubble gathers data and pictures from celestial objects, its computers send the digitized information to Earth as radio signals. The HST signal is passed through a series of **satellite** relays, then to the Goddard Space Flight Center in Maryland before reaching the Space Telescope Science Institute at Johns Hopkins University. Here, the signal is converted back into pictures and data. Scientists at these institutions are responsible for the daily programming and operations of the HST.

Scheduled to serve until the year 2010, the Hubble Space Telescope continues to provide dramatic observations that stretch the boundaries of the known universe. Among its accomplishments so far, the HST has provided evidence of the existence of massive black holes at the centers of galaxies, captured the first detailed image of the surface of Pluto, detected protogalaxies (structures presently thought to have existed close to the time of the origin of the universe), and captured spectacular images of the comet Shoemaker-Levy as its parts collided with Jupiter.

In order to provide continuous and broader astronomical observations, NASA is expected to launch the Hubble's successor (tentatively named the Next Generation Space Telescope) more fully equipped with cameras and spectrographs sensitive to multiple regions of the **electromagnetic spectrum** prior to the end of the HST's expected service life.

See also Big Bang theory; Cosmology; History of manned space exploration; Quasars; Solar system; Spacecraft, manned; Stellar life cycle

HUMBOLDT, ALEXANDER VON

(1769-1859)

German explorer and naturalist

Alexander Humboldt pursued a lifetime of exploration and discovery, and was best known for his expeditions to Central and **South America**. A master of observation and analysis, Humboldt was also a prolific writer and recorder of his observed scientific data.

Humboldt was born in Berlin, the son of a Prussian army officer and a Huguenot (French Protestant) mother. He experienced poor health as a child and was unimpressive as a student. He was raised under his mother's strict Calvinistic beliefs and remained unmarried throughout his life.

Perhaps his most notable accomplishment was his five-year expedition to South and Central America made from 1799 to 1804. Spain had been preoccupied with the pursuit of wealth and conquest in its American colonies, and it was rare for a learned individual like Humboldt to gain permission to visit these areas. Once there, his perseverance took him to the edges of human endurance.

South America was a largely unknown land, and much of what Humboldt observed was new knowledge. Traveling by foot and canoe, he discovered a connection between the Orinoco and Amazon River systems. He climbed volcanoes in Ecuador and observed how they were positioned in a line, as though following a flaw in the earth's **crust**. He collected thousands of plant specimens. He observed ocean currents in the Pacific Ocean including one, now called the Peru Current, which was also named after him. No matter where his location or surroundings, Humboldt tirelessly recorded his observations. This proved to be Humboldt's greatest legacy.

Humboldt resided in Paris from 1805 to 1827, enjoying a cosmopolitan lifestyle that allowed him to associate with many of his fellow professionals. He published more than 30 volumes of his data during this time, proving his excellence as a writer and artist.

Humboldt spent his later years in Berlin, where he had become a notable figure. At the invitation of the Russian government, he traveled for three months in the Urals and Siberia, and brought with him his knowledge of mining techniques.

The ceremonial trappings of this visit only interfered with his ability to observe the region.

Humboldt died while working on the fifth volume of his book *Kosmos*. This work was his attempt to give a unified explanation of all existence, and gathered most of the available scientific knowledge of the time. During his life, Humboldt had been a meteorologist, botanist, geologist, geographer, and oceanographer.

See also Cosmology; Ocean circulation and currents

HUMIDITY

Humidity is a measure of the quantity of **water** vapor in the air. There are different methods for determining this quantity and those methods are reflected in a variety of humidity indexes and readings.

The humidity reading in general use by most meteorologists is relative humidity. The relative humidity of air describes the saturation of air with water vapor. Given in terms of percent humidity (e.g., 50% relative humidity), the measurement allows a comparison of the amount of water vapor in the air with the maximum amount water vapor that—at a given temperature—represents saturation. Saturation exists when the **phase state changes** of **evaporation** and **condensation** are in equilibrium.

Approximately one percent of Earth's total water content is suspended in the atmosphere as water vapor, **precipitation**, or **clouds**. Humidity is a measure only of the vapor content.

Because water vapor exerts a pressure, the presence of water vapor in the air contributes vapor pressure to the overall **atmospheric pressure**. Actual vapor pressures are measured in millibars. One atmosphere of pressure (1 atm) equals 1013.25 mbar.

In contrast to the commonly used relative humidity, the absolute humidity is a measure of the actual mass of water vapor in a defined volume of air. Absolute humidity is usually expressed in terms of grams of water per cubic meter.

Specific humidity is a measure of the mass of water vapor in a defined volume of air relative to the total mass of gas in the defined volume.

The amount of water vapor needed to achieve saturation increases with **temperature**. Correspondingly, as temperature decreases, the amount of water vapor needed to reach saturation decreases. As the temperature of a parcel of air is lowered it will eventual reach saturation without the addition or loss of water mass. At saturation (**dew point**) condensation or precipitation. This is the fundamental mechanism for cloud formation as air moving aloft is cooled. The level of cloud formation is an indication of the humidity of the ascending air because—given the standard temperature lapse rate—a parcel of air with a greater relative humidity will experience condensation (e.g., cloud formation) at a lower altitude than a parcel of air with a lower relative humidity.

The differences in the amount of water vapor in a parcel of air can be dramatic. A parcel of air near saturation may contain 28 grams of water per cubic meter of air at 30°F (–1°C), but only 8 grams of water per cubic meter of air at 10°F (–12°C).

An increasingly popular measure of comfort, especially in the hotter summer months, is the heat index. The heat index is an integrated measurement of relative humidity and dry air temperature. The measurement is useful because higher humidity levels retard evaporation from the skin (perspiration) and lower the effectiveness of physiological cooling mechanisms.

Absolute humidity may be measured with a sling cyclometer. A hydrometer is used to measure water vapor content. Water vapor content can also be can be expressed as grains/cubic ft. A grain, a unit of weight, equals 1/7000 of a pound.

See also Adiabatic heating; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pressure; Hydrologic cycle; Hydrostatic pressure; Weather forecasting methods; Weather forecasting; Wind chill

HURRICANE • *see* TROPICAL CYCLONE

HUTTON, JAMES (1726-1797)

Scottish physician

James Hutton, a Scottish physician and farmer, is considered by many to be the father of **geology**. Hutton observed geological changes and theorized that the forces that were changing the landscape of his farm were the same forces that had changed Earth's surface in the past. He built on this theory to form his principle of uniformitarianism in 1785.

The principle states that current geological processes, for example volcanic activity and **erosion**, are the same processes that were at work in the past, and will still be at work in the future. A summary of his theory is the phrase "the present is the key to the past." Hutton watched these slow changes occurring on his own farm and theorized that over time, a stream could carve a valley, rain would erode **rock**, and sediment could accumulate and form new **landforms**. He realized that these forces must be acting very slowly, and therefore, Earth must be older than theologians at the time argued it to be. He published this theory in 1790 in his work *The Theory of the Earth*.

Modern evidence supports the essential elements of Hutton's theory. Earth is approximately 4.6 billion years old, and there is abundant evidence that slow processes have worked to mold and shape the planet. Moreover, the same forces that acted in the past are active now, even though the relative rates may vary over time. When Hutton published his theories, however, they were not met with enthusiasm. **Uniformitarianism** went against both religious beliefs and the theory of **catastrophism**, the accepted theory of the time. Catastrophism states that the earth was formed not by slow processes, but by violent, worldwide disturbances such as earthquakes and **floods**. It was not until the nineteenth century that Sir **Charles Lyell**, in his 1830 work *Principles of Geology*, popularized the theory of uniformitarianism.

James Hutton was not only known for his uniformitarianism theory, but also for developing the concept of the rock cycle. This theory describes the interrelationships between igneous, sedimentary, and metamorphic rocks. The matter that makes up these rocks is neither created nor destroyed, but instead transformed from one rock type to another. He also suggested that the study of the earth be called "geophysiology." Hutton's theories about Earth as an entity that undergoes dynamic cycles are considered by some to be the basis of the **Gaia hypothesis**, the concept of the "living earth."

See also Earth (planet); Geologic time

HYDROCARBONS

Hydrocarbons are compounds composed solely of **carbon** and hydrogen. Despite their simple composition, hydrocarbons include a large number of different compounds with a variety of chemical properties. Hydrocarbons are derived from oil deposits, and are the source of gasoline, heating oil, and other "fossil fuels." Found in a variety of geological settings, hydrocarbons provide the carbon skeletons required for the thousands of chemicals produced by the chemical industry.

Hydrocarbons are classified on the basis of their structure and bonding. The three major classes are aliphatics, alicyclics, and aromatics. Aliphatics have carbon backbones that form straight or branched chains, with no rings. Alicyclics are ring compounds that, while they may have one or more double bonds, do not form conjugated sets of double bonds around the ring like benzene. Aromatics are compounds with at least one benzene ring. Aliphatic means fatty, and aromatic refers to odor, but these terms no longer have significance for the compounds they describe.

Because hydrocarbons are nonpolar, they are generally insoluble in **water**, and dissolve in nonpolar solvents.

The aliphatic hydrocarbons are further divided into alkanes, alkenes, and alkynes. Alkanes (sometimes called paraffins) have only single bonds, while alkenes (sometimes called olefins) have a carbon-carbon double bond, and alkynes have a carbon-carbon triple bond. Compounds with two double bonds are known as dienes. Compounds with double or triple bonds are referred to as "unsaturated," while those without are "saturated," meaning all of their carbons are bonded to the maximum number of hydrogens.

All alkanes have the general formula C_nH_{2n+2}, where n is the number of carbon atoms in the compound. Alkenes have the formula C_nH_{2n}, while alkynes are C_nH_{2n-2}. Because of these regularities, the members of each group are known as a homologous series.

The simplest alkane (and indeed, the simplest hydrocarbon) is methane, CH_4. The four C-H bonds are directed towards the four corners of a tetrahedron, with carbon at its center and hydrogens at each vertex. The C-H bonds are slightly polar, and equivalent in length and strength. The angle formed by any pair of bonds is 109.5 degrees, the tetrahedral angle.

Despite the bond polarity, there is no net dipole because of the symmetry of the molecule, and methane has very weak intermolecular attractions, consisting only of van der Waals attractions. These attractions are proportional to surface **area**, which is small for the compact methane molecule and, as a result, methane has a very low **melting** point and boiling point, –297.4°F (–183°C) and –258.7°F (–161.5°C), respectively.

Methane is found in oil deposits, forming the majority of the "natural gas" fraction. Methane is also formed by certain anaerobic bacteria, especially in swamp bottoms, where it bubbles to the surface as "marsh gas." It is used in large quantities as fuel for heating and cooking because it burns with **oxygen** to produce **carbon dioxide** and water. Methane burns cleanly, with very little soot or smoke.

The next alkane is ethane, C_2H_6. Its higher melting and boiling points (–277.6°F [–172°C] and –127.3°F [–88.5°C], respectively) reflect its larger surface area and consequently greater van der Waals attraction.

Propane, C_3H_8, is an important fuel because it can be liquified at pressures low enough to easily maintain in commercial and consumer apparatus, allowing easy transport and storage, but vaporizes to burn almost as cleanly as methane.

Higher alkanes continue the trend of increased surface area and higher melting and boiling points. However, as the number of carbon atoms increases, structural isomerism becomes possible, allowing the same molecular formula to describe two or more compounds with different structures and different physical properties. For example, Butane (C_4H_{10}) can be either a straight-chain molecule, or a branched one, with three carbons in a straight chain and the fourth branching off from the middle carbon. Compounds with the same molecular formula but with different three-dimensional structures are called isomers. The straight chain isomer is called n-butane (for "normal"), while the branched one is called either iso-butane, or 2-methyl propane. This latter name indicates that the longest straight-chain backbone within the molecule has three carbons (propane), and there is a single-carbon branch (methyl) at the second position in the main chain. The extended structure of n-butane gives it a boiling point of 32°F (0°C), while the more spherical iso-butane boils twelve degrees lower, at 10.4°F (–12°C), due to its smaller surface area. As the number of carbons increase, so too does the number of possible isomers.

The simplest alkene is ethene, C_2H_4, also called ethylene. Ethene is a planar molecule, with the four hydrogens splayed out in a plane and angles between bonds of 120 degrees. Ethene melts at –272.2°F (–169°C), and boils at –151.6°F (–102°C).

Higher alkenes take their names from the corresponding alkanes: propene, butene, pentene, etc. However, beginning with butene, isomerism is possible based on the position of the double bond. If the bond is between C1 and C2, the compound is 1-butene, while if it lies between C2 and C3, it is 2-butene (the compound with a double bond between C3 and C4 is equivalent to 1-butene). In addition, the non-rotation of the double bond means there are two structural isomers of 2-butene, one with the two terminal carbons on the same side of the C=C long axis, termed *cis*-2-butene, and one with them on opposite sides, *trans*-2-butene. As might be expected, the number of possible isomers rises with an increase in number of carbons.

The chemical reactions of the alkenes is more complex and richer than that of the alkanes, due to the presence of the double bond. The most common reaction is of addition across the double bond. For instance, addition of water to ethene creates ethyl alcohol. Alkenes are often prepared by the reverse of this reaction, dehydration across the double bond.

Alkynes have a triple bond. The simplest alkyne is C_2H_2, athyne, also called acetylene. Acetylene is an important high-temperature fuel used especially for metal cutting.

Cyclic alkenes, such as cyclohexene (C_6H_{10}), are common solvents, and also serve as starting points for a number of organic syntheses.

Benzene (C_6H_6) is a cyclohexane (the carbons are bonded in a ring) with three double bonds alternating around the ring. The electrons in benzene's bonds are highly delocalized, to the point that it is no longer accurate to describe them as belonging to individual carbons. Instead, they form a cloud "ring" above and below the plane of the carbons and, as a result, all the carbon-carbon bonds are of equivalent length and strength.

See also Atomic theory; Fuels and fuel chemistry; Geochemistry; Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration; Petroleum

HYDROGEOLOGY

Hydrogeology is the study of **water** contained in materials of Earth's **crust**, the physical and chemical characteristics of this water, its origin, **evolution**, and ultimate destination. Hydrogeology is the term used by geologists and hydrogeologists for this study. Geohydrology is the term most often used by engineers. The two terms are roughly equivalent.

The water contained in materials of Earth's crust is called **groundwater** (sometimes spelled as "ground water" to distinguish ground water from surface water). Groundwater is sometimes defined as water below the earth's surface, but groundwater may occur at the surface especially after heavy rainfall in certain areas.

When groundwater is not at the earth's surface, there is a zone beneath the surface where the majority of pore (open) spaces are filled with air. This is called the vadose zone or zone of aeration. Below a certain depth, all the pore spaces are filled with water. This is known as the phreatic zone or zone of saturation. The zone of saturation extends downward until pressure of the overlying materials is so great that there are no pore spaces available. The **area** separating the vadose and phreatic zones is called the **water table**, which is usually represented on cross sections as a dashed line. The dashed line, as opposed to a solid line, indicates that the water table moves up and down with the **seasons**, being higher and nearer Earth's surface during wet seasons and lower and deeper below Earth's surface during dry seasons.

Modern groundwater studies have their origin in the middle 1850s when a French engineer, Henry Darcy, published a report describing an experiment he conducted with a tube on an incline that he had filled with **sand**. Darcy's experiments led to the first quantitative "law" in hydrogeology, used to determine the rate of flow of groundwater and now known as Darcy's law. It can be expressed mathematically as $v = KIA$, where "v" equals the rate of groundwater flow, "K" equals hydraulic conductivity or **permeability**, "A" equals the area of a cross-section of the water-bearing unit (e.g., cross-section of Darcy's cylinder of sand) and "I" equals the hydraulic gradient.

Hydraulic conductivity or permeability (K) is measured from the material through which the groundwater is flowing and has the dimensions of length per unit time (L/T, e.g., cm per second, feet per year, etc.).

Groundwater occurs underground in bodies of Earth materials called aquifers, which may be of two types: unconfined or confined. Unconfined aquifers are bound at their top by the water table. Confined aquifers are bound both top and bottom by materials through which little or no water flows, (i.e., impermeable materials), or aquicludes (also known as aquitards). The materials holding the water are usually inclined to the horizontal so that pressure builds up in the **aquifer**. When the aquifer is drilled, the water rises to the highest level of water confined within the aquifer or sometimes to the surface. These aquifers represent a special kind of aquifer, called **artesian**, after an area in France where this situation is common.

Hydrogeology is extremely important to mankind because over 100 million people in the United States alone use groundwater for drinking; about a third of the largest U.S. cities have some reliance upon groundwater use in their potable (drinkable) water supply.

It is not always easy to gather data about groundwater in a given area because evidence of underlying water is not usually readily apparent at the surface. Therefore, it is necessary to drill wells into and below the water table into the phreatic zone (zone of saturation). Well drilling is a time-consuming and expensive method for gathering data and is usually not done solely for academic purposes. It is usually done to meet the requirements of state or federal regulatory agencies. Such studies are sometimes financed by the agencies but, in most cases, they are financed by private industry seeking to avoid contamination by the use of proper hydrogeologic profile maps, or to determine the presence and/or extent of existing contamination. In the United States, the federal government, especially the Department of Defense and the Department of Energy, have industrial facilities that are responsible for groundwater cleanup.

The United States Congress passed two major laws that have greatly impacted the study of groundwater: the Resource Conservation and Recovery Act (RCRA) of 1976 and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980.

RCRA establishes a "cradle to grave" tracking system for hazardous wastes and requires those facilities considered RCRA facilities to define and characterize the uppermost aquifer beneath the facility and to monitor the quality of the groundwater as it flows beneath the facility. Numerous wells are usually required to characterize the uppermost aquifer and, in every case, at least four wells are required (one upgradient and three downgradient from the facility).

CERCLA was originally conceived to allow for cleanup of abandoned hazardous waste sites. It established a fund to be raised and maintained by collecting a tax on the producers of hazardous materials. This fund (and the act) soon became known as "Superfund." Superfund was reauthorized and greatly enhanced in 1986 by the Superfund Amendments and Reauthorization Act (SARA).

Once groundwater is contaminated, it can be very costly and time consuming to remediate (i.e., clean up). Unfortunately, one of the most common groundwater contaminants is also one of the most difficult to remediate—the chemical group known as the chlorinated solvents, especially trichloroethylene (TCE) and perchloroethylene (PCE). These have been widely used as solvents, TCE as a degreaser and PCE in the dry cleaning industry. They do not fully dissolve in groundwater and they tend to form pockets or globules in both the vadose and phreatic zones.

One of the most common methods of cleaning up groundwater is the "pump and treat" method whereby groundwater is pumped to the surface, treated by some method, then reinjected into the aquifer or released as surface water. This does not work well with TCE and PCE because as the groundwater is pumped to the surface, these globules remain in the subsurface and they fail to come to the surface with the groundwater.

See also Drainage basins and drainage patterns; Drainage calculations and engineering; Freshwater; Hydrostatic pressure; Petroleum, detection; Porosity and permeability; Relief; Remote sensing; Runoff; Seismology; Waste disposal; Wastewater treatment; Water pollution and biological purification

HYDROLOGIC CYCLE

The hydrologic, or **water**, cycle is the continuous, interlinked circulation of water among its various compartments in the environment. Hydrologic budgets are analyses of the quantities of water stored, and the rates of transfer into and out of those various compartments. A simplified hydrologic cycle starts with heating caused by **solar energy** and progresses through stages of **evaporation** (or sublimation), **condensation**, **precipitation** (snow, rain, hail, glaze), **groundwater**, and **runoff**.

The most important places in which water occurs are the **oceans**, **glaciers**, underground aquifers, surface waters, and the atmosphere. The total amount of water among all of these compartments is a fixed, global quantity. However, water moves readily among its various compartments through the processes of evaporation, precipitation, and surface and subsurface flows. Each of these compartments receives inputs of water and has corresponding outputs, representing a flow-through system. If there are imbalances between inputs and outputs, there can be significant changes in the quantities stored locally or even globally. An example of a local change is the **drought** that can occur in **soil** after a long period without replenishment by precipitation. An example of a global change in hydrology is the increasing mass of continental **ice** that occurs during glacial epochs, an event that can remove so much water from the oceanic compartment that sea level can decline by more than 328 ft (100 m), exposing vast areas of **continental shelf** for the development of terrestrial ecosystems.

Estimates have been made of the quantities of water that are stored in various global compartments. By far, the largest quantity of water occurs in the deep **lithosphere**, which contains an estimated 27×10^{18} tons (27-billion-billion tons) of water, or 94.7% of the global total. The next largest compartment is the oceans, which contain 1.5×10^{18} tons, or 5.2% of the total. Ice caps contain 0.019×10^{18} tons, equivalent to most of the remaining 0.1% of Earth's water. Although present in relatively small quantities compared to the above, water in other compartments is very important ecologically because it is present in places where biological processes occur. These include shallow groundwater (2.7×10^{14} tons), inland surface waters such as **lakes** and **rivers** (0.27×10^{14} ton), and the atmosphere (0.14×10^{14} tons).

The smallest compartments of water also tend to have the shortest turnover times, because their inputs and outputs are relatively large in comparison with the mass of water that is contained. This is especially true of atmospheric water, which receives annual inputs equivalent to 4.8×10^{14} tons as evaporation from the oceans (4.1×10^{14} tons/yr) and terrestrial ecosystems (0.65×10^{14} tons/yr), and turns over about 34 times per year. These inputs of water to the atmosphere are balanced by outputs through precipitation of rain and snow, which deposit 3.7×10^{14} tons of water to the surface of the oceans each year, and 1.1×10^{14} tons/yr to the land.

These data suggest that the continents receive inputs of water as precipitation that are 67% larger than what is lost by evaporation from the land. The difference, equivalent to 0.44×10^{14} tons/yr, is made up by 0.22×10^{14} tons/yr of runoff of water to the oceans through rivers, and another 0.22×10^{14} tons/yr of subterranean runoff to the oceans.

The movements of water in the hydrologic cycle are driven by gradients of energy. Evaporation occurs in response to the availability of thermal energy and gradients of concentration of water vapor. The ultimate source of energy for most natural evaporation of water on Earth is solar electromagnetic radiation. Heating from within Earth's mantle and **crust** that results from radioactive decay supplies the other thermal energy requirements. Solar energy is absorbed by surfaces, increasing their heat content, and thereby providing a source of energy to drive evaporation. In contrast, surface and ground waters flow in response to gradients of gravitational potential. In other words, unless the flow is obstructed, water spontaneously courses downhill.

Clouds forming over water. © *Joseph Sohm/Corbis. Reproduced by permission.*

The hydrological cycle of a defined **area** of landscape is a balance between inputs of water with precipitation and upstream drainage, outputs as evaporation and drainage downstream or deep into the ground, and any internal storage that may occur because of imbalances of the inputs and outputs. Hydrological budgets of landscapes are often studied on the spatial scale of watersheds, or the area of terrain from which water flows into a stream, river, or lake.

The simplest watersheds are so-called headwater systems that do not receive any drainage from watersheds at higher altitude, so the only hydrologic input occurs as precipitation, mostly as rain and snow. However, at places where **fog** is a common occurrence, windy conditions can effectively drive tiny atmospheric droplets of water vapor into the forest canopy, and the direct deposition of cloud water can be important.

Vegetation can have an important influence on the rate of evaporation of water from watersheds. This hydrologic effect is especially notable for well-vegetated ecosystems such as **forests**, because an extensive surface area of foliage supports especially large rates of transpiration. Evapotranspiration refers to the combined rates of transpiration from foliage, and evaporation from non-living surfaces such as moist soil or surface waters. Because transpiration is such an efficient means of evaporation, evapotranspiration from any well vegetated landscape occurs at much larger rates than from any equivalent area of non-living surface.

In the absence of evapotranspiration an equivalent quantity of water must drain from the watershed as seepage to deep groundwater or as streamflow.

Forested watersheds in seasonal climates display large variations in their rates of evapotranspiration and streamflow. This effect can be illustrated by the seasonal patterns of hydrology for a forested watershed in eastern Canada. The input of water through precipitation is 58 in (146 cm) per year, but 18% of this arrives as snow, which tends to accumulate on the surface as a persistent snow pack. About 38% of the annual input is evaporated back to the atmosphere through evapotranspiration, and 62% runs off as river flow. Although there is little seasonal variation in the input of water with precipitation, there are large seasonal differences in the rates of evapotranspiration, runoff, and storage of groundwater in the watershed. Evapotranspiration occurs at its largest rates during the growing season and runoff is therefore relatively sparse during this period. In fact, in small watersheds in this region forest streams can literally dry up because so much of the precipitation input and soil water is utilized for evapotranspiration, mostly by trees. During the autumn, much of the precipitation input serves to recharge the depleted groundwater storage, and once this is accomplished stream flows increase again. Runoff then decreases during winter, because most of the precipitation inputs occur as snow, which accumulates on the ground surface because of the prevailing sub-freezing temperatures. Runoff is largest during the early springtime when warming temperatures cause the snow pack to melt during a short period of time, resulting in a pronounced flush of stream and river flow.

Some aspects of the hydrologic cycle can be utilized by humans for a direct economic benefit. For example, the potential energy of water elevated above the surface of the oceans can be utilized for the generation of **electricity**. However, the development of hydroelectric resources generally causes large changes in hydrology. This is especially true of hydroelectric developments in relatively flat terrain, which require the construction of large storage reservoirs to retain seasonal high-water flows, so that electricity can be generated at times that suit the peaks of demand. These extensive storage reservoirs are essentially artificial lakes, sometimes covering enormous areas of tens of thousands of hectares. These types of hydroelectric developments cause great changes in river hydrology, especially by evening out the variations of flow, and sometimes by unpredictable spillage of water at times when the storage capacity of the reservoir is full. Both of these hydrologic influences have significant ecological effects, for example, on the habitat of salmon and other aquatic biota.

Where the terrain is suitable, hydroelectricity can be generated with relatively little modification to the timing and volumes of water flow. This is called run-of-the-river hydroelectricity, and its hydrologic effects are relatively small. The use of geologically warmed ground water to generate energy also has small hydrological effects, because the water is usually re-injecting back into the **aquifer**.

Human activities can influence the hydrologic cycle in many other ways. The volumes and timing of river flows can be greatly affected by channeling to decrease the impediments to flow, and by changing the character of the watershed by paving, compacting soils, and altering the nature of the vegetation. Risks of flooding can be increased by speeding the rate at which water is shed from the land, thereby increasing the magnitude of peak flows. Risks of flooding are also increased if **erosion** of soils from terrestrial parts of the watershed leads to siltation and the development of shallower river channels, which then fill up and spill over during high-flow periods. Massive increases in erosion are often associated with deforestation, especially when natural forests are converted into agriculture.

The quantities of water stored in hydrologic compartments can also be influenced by human activities. An important example of this effect is the mining of groundwater for use in agriculture, industry, or for municipal purposes. The best-known case of groundwater mining in **North America** concerns the enormous Ogallala aquifer of the southwestern United States, which has been drawn down mostly to obtain water for irrigation in agriculture. This aquifer is largely comprised of “fossil water” that was deposited during earlier, wetter climates, although there is some recharge capability through rain-fed groundwater flows from mountain ranges in the watershed of this underground reservoir.

Sometimes industrial activities lead to large emissions of water vapor into the atmosphere, producing a local hydrological influence through the development of low-altitude **clouds** and fogs. This effect is mostly associated with electric power plants that cool their process water using cooling towers.

A more substantial hydrologic influence on evapotranspiration is associated with large changes in the nature of vegetation over a substantial part of a watershed. This is especially important when mature forests are disturbed, for example, by wildfire, clear-cutting, or conversion into agriculture. Disturbance of forests disrupts the capacity of the landscape to sustain transpiration, because the amount of foliage is reduced. This leads to an increase in stream flow volumes, and sometimes to an increased height of the groundwater table. In general, the increase in stream flow after disturbance of a forest is roughly proportional to the fraction of the total foliage of the watershed that is removed (this is roughly proportional to the fraction of the watershed that is burned, or is clear-cut). The influence on transpiration and stream flow generally lasts until regeneration of the forest restores another canopy with a similar area of foliage, which generally occurs after about 5–10 years of recovery. However, there can be a longer-term change in hydrology if the ecological character of the watershed is changed, as occurs when a forest is converted to agriculture.

See also Alluvial systems; Aquifer; Artesian; Atmospheric composition and structure; Hydrogeology; Hydrologic cycle; Hydrostatic pressure; Hydrothermal processes; Stream capacity and competence; Stream piracy; Troposphere and tropopause; Wastewater treatment; Water pollution and biological purification; Water table; Water

HYDROSTATIC PRESSURE

Hydrostatic pressure is a state of stress characterized by equal principal stresses, $S_1 = S_2 = S_3$. This is the state of stress that exists at any point in a liquid at rest. Units of measurement are pounds per square inch (psi) in the English System and megabars (Mb) in the International System. The concept of hydrostatic pressure or stress is very important to many disciplines of physical science and engineering. Geologists often consider pore fluid pressure in rocks as hydrostatic, as if the fluid is part of a column of **water** open to the surface. Well drilling engineers must know whether the pore fluid pressure at depth is normal hydrostatic, overpressured, or underpressured to design the fluid system used to drill the wells. A correct design minimizes the dangers of blowout or formation damage. The mechanical behavior of rocks depends, in part, on the hydrostatic pressure (also called confining pressure or mean stress) part of the total stress (the sum of the mean stress and shear stresses) acting on the **rock**. In general, brittle rock strength increases with increase in hydrostatic stress.

Hydrostatic pressure is a scalar quantity because it does not vary with direction. The magnitude of hydrostatic pressure P at any point in a liquid is determined by the height of the column of liquid above the point and the density of the liquid. Hydrostatic pressure P varies with depth according to the linear relationship, $P = \rho gh$, where ρ is the fluid density, g is the **gravitational constant**, and h is the depth of the column of fluid to the measured point. If water is the fluid, the hydrostatic pressure gradient is: P = ρgh = 0.4 psi/foot (9.8 kPa/m). The state of stress in liquids is hydrostatic because fluids do not support any shear stress (any differences among the principal stresses). In general, the stress state in rocks of the upper **crust** is not hydrostatic because solids support shear stress. Many **petroleum** engineers assume the state of stress at depth in the earth is hydrostatic to simplify their calculations.

See also Hydrogeology

HYDROTHERMAL PROCESSES

Any subsurface encounter between **water** and heat produces a hydrothermal process. The heat is usually supplied by upwellings of **magma** from the mantle, the water by **precipitation** that percolates downward through surface rocks. Some oceanic water enters the mantle at subduction zones and becomes an important ingredient in upper-mantle magmas.

Most hydrothermal processes are driven by convection. Convection occurs because water, like most substances, expands when heated. The result is that hot water rises and cool water sinks. Convection occurs when any water-permeated part of the earth's **crust** is heated from below: heated water fountains upward over the hot spot and cool water descends around its edges. These movements occur through cracks and channels in the **rock**, forcing the water to move slowly and remain in constant contact with various **minerals**. Water convecting through rock is thus an effective means of dissolving, transporting, and depositing minerals. Most deposits of concentrated minerals, including large, shapely **crystals**, are created by hydrothermal processes.

Some manifestations of hydrothermal processes are dramatic, including the geysers and hot **springs** that sometimes occur where shallow magma is present. However, most hydrothermal circulation occurs inconspicuously in the vicinity of large magmatic intrusions. These can cause water to convect through the rocks for miles around.

Along the **mid-ocean ridges**, for example, the heat of the magma that rises continuously from the mantle to form new oceanic crust causes water to convect through the top mile or two (2–3 km) of oceanic crust over many thousands of square miles. Down-convected ocean water encounters hot rocks at depth, is heated, yields up its dissolved magnesium, and leaches out manganese, copper, calcium, and other **metals**. This hot, chemically altered brine then convects upward to the ocean floor, where it is cooled and its releases most of its dissolved minerals as solid precipitates. This process makes the concentrations of vanadium, cobalt, nickel, and copper in recent sea-floor sediments near mid-ocean ridges 10–100 times greater than those elsewhere, and has formed many commercially important ores.

Two of the metals transported in large quantities by seafloor circulation (i.e., calcium and magnesium) are important controllers of the **carbon dioxide** (CO_2) balance of the ocean and thus of the atmosphere. A volume of water approximately equal to the world's **oceans** passes through the hydrothermal mid-ocean ridge cycle every 20 million years.

See also Fumarole; Geyser; Mid-ocean ridges and rifts; Seafloor spreading

HYDROTHERMAL VENTS • *see* HYDROTHERMAL PROCESSES

HYPERSPECTRAL SENSORS • *see* MAPPING TECHNIQUES

I

ICE

Ice is frozen **water**, or in other words, water in solid state. Ice is a transparent, colorless substance with some special properties; it floats in water, ice expands when water freezes, and its **melting** point decreases with increasing pressure. Water is the only substance that exists in all three phases as gas, liquid, and solid under normal circumstances on Earth.

Water, and thus ice molecules, consist of one **oxygen** and two hydrogen atoms. Water is a polar molecule, with a slight negative charge on the oxygen side, and a slight positive charge on the hydrogen side, which makes it possible to interact with other polar molecules or ions. Thus, a loose chemical connection called a hydrogen bond forms between the water molecules, where each water molecule can bind to other water molecules, forming a complex network. These hydrogen bonds are the main reason for the special properties of water and ice.

Water in the solid state forms a highly ordered hexagonal (six-sided) crystal lattice structure, because it is the most stable arrangement of the water molecules. Although the individual molecules can vibrate, they cannot move fast enough to leave the crystal structure, since the opposite electrical polarities hold them together. This lattice crystal can be visualized as layers of hexagonal rings of the oxygen atoms stacked on each other. Ice has eleven known crystal forms, depending on pressure, **temperature**, or how quickly the ice forms. Ice cannot form from liquid water at the **freezing** point, unless there are seeds for the crystal, which dissipate the energy of the colliding water molecules, keeping them locked in the lattice structure. If no seeds are present, spontaneous crystal nucleation begins only if the water is supercooled below the freezing point.

Ice is present in nature in many places and in many forms: **icebergs**, ice sheets, **glaciers**, snow, freezing rain, sleet, ice **crystals**, icicles, hail, rime, graupel, and ice **fog**. Ice plays an important role in **erosion** (water fills the cracks of **rock**, freezes, expands, and breaks the rock), and in atmospheric energy transport (when water vapor changes into liquid or ice, latent heat is released). The way ice forms in bodies of water (not from the bottom up, but from the top down) protects many organisms in the water from very cold and fast temperature fluctuations.

Ice forming on water. ***Robert J. Huffman. Field Mark Publications. Reproduced by permission.***

ICE AGES

The **ice** ages were periods in Earth's history during which significant portions of the earth's surface were covered by **glaciers** and extensive fields of ice. Scientists often use more specific terms for an ice "age" depending on the length of time it lasts. It appears that over the long expanse of Earth history, seven major periods of severe cooling have occurred. These periods are often known as ice eras and, except for the last of these, are not very well understood.

What is known is that the earth's average annual **temperature** varies constantly from year to year, from decade to decade, and from century to century. During some periods, that average annual temperature has dropped to low enough levels for fields of ice to grow and cover large regions of the earth's surface. The seven ice eras have covered an average of about 50 million years each.

The ice era that scientists understand best (because it occurred most recently) began about 65 million years ago. Throughout that long period, the earth experienced periods of alternate cooling and warming. Those periods during which the annual temperature was significantly less than average are known as ice epochs. There is evidence for the occurrence of six ice epochs during this last of the great ice eras.

During the 2.4 million-year lifetime of the last ice epoch, about two dozen ice ages occurred. That means that the earth's average annual temperature fluctuated upwards and downwards to a very significant extent about two dozen times during the 2.4 million-year period. In each case, a period of significant cooling was followed by a period of significant warming—an interglacial period after which cooling once more took place.

Scientists know a great deal about the cycle of cooling and warming that has taken place on the earth over the last 125,000 years, the period of the last ice age cycle. They have been able to specify with some degree of precision the centuries and decades during which ice sheets began to expand and diminish. For example, the most severe temperatures during the last ice age were recorded about 50,000 years ago. Temperatures then warmed before plunging again about 18,000 years ago.

Clear historical records are available for one of the most severe recent cooling periods, a period now known as the Little Ice Age. This period ran from about the fifteenth to the nineteenth century and caused widespread crop failure and loss of human life throughout **Europe**. Since the end of the Little Ice Age, temperatures have continued to fluctuate with about a dozen unusually cool periods in the last century, interspersed between periods of warmer **weather**. Scientists are not certain as to whether the last ice age has ended, or continues to the present.

A great deal of what scientists know about the ice ages they have learned from the study of mountain glaciers. For example, when a glacier moves downward out of its mountain source, it carves out a distinctive shape on the surrounding land. The "footprints" left by continental glaciers formed during the ice ages are comparable to those formed by mountain glaciers.

The transport of materials from one part of the earth's surface to another part is also evidence for the formation of continental glaciers. Rocks and **fossils** normally found only in one region of the earth may be picked up, moved by ice sheets, and deposited elsewhere. The "track" left by the moving glacier provides evidence of the ice sheets movement. In many cases, the moving ice may actually leave scratches on the **rock** over which it moves, providing further evidence for changes that took place during an ice age.

Scientists have been asking what the causes of ice ages are for more than a century. The answer (or answers) to that question appears to have at least two main parts: astronomical factors and terrestrial factors. By astronomical factors scientists mean that the way the earth is oriented in **space**, which can determine the amount of heat it receives and, hence, its annual average temperature.

One of the most obvious astronomical factors about which scientists have long been suspicious is the appearance of sunspots. Sunspots are eruptions that occur on the Sun's surface during which unusually large amounts of **solar energy** are released. The number of sunspots that occur each year changes according to a fairly regular pattern, reaching a maximum about every eleven years or so. The increasing and decreasing amounts of energy sent out during sunspot maxima and minima, some scientists have suggested, may contribute in some way to the increase and decrease of ice fields on the earth's surface.

By the beginning of the twentieth century, however, astronomers had identified three factors that almost certainly are major contributors to the amount of solar radiation that reaches the earth's surface and, hence, the earth's average annual temperature. These three factors are the earth's angular tilt, the shape of its orbit around the **Sun**, and its axial precession.

The first of these factors, the planet's angular tilt, is the angle at which its axis is oriented to the plane of its orbit around the Sun. This angle slowly changes over time, ranging between 21.5 and 24.5 degrees. At some angles, the earth receives more solar radiation and becomes warmer, and at other angles it receives less solar radiation and becomes cooler.

The second factor, the shape of the earth's orbit around the Sun, is important because, over long periods of time, the orbit changes from nearly circular to more elliptical (flatter) in shape. Because of this variation, the earth receives solar radiation in varying amounts depending on the shape of its orbit. The final factor, axial precession, is a "wobble" in the orientation of the earth's axis to its orbit around the Sun. As a result of axial precession, the amount of solar radiation received during various parts of the year changes over very long periods of time.

Between 1912 and 1941, the Yugoslav astronomer Milutin Milankovitch developed a complex mathematical theory that explained how the interaction of these three astronomical factors could contribute to the development of an ice age. His calculations provided rough approximations of the occurrences of ice ages during the earth history.

Astronomical factors provide only a broad general background for changes in the earth's average annual temperature, however. Changes that take place on the earth itself also contribute to the temperature variations that bring about ice ages.

Scientists assert that changes in the composition of the earth's atmosphere can affect the planet's annual average temperature. Some gases, such as **carbon dioxide** and nitrous oxide, have the ability to capture heat radiated from the earth, warming the atmosphere. This phenomenon is known as the **greenhouse effect**. But the composition of the earth's atmosphere is known to have changed significantly over long periods of time. Some of these changes are the result of complex interactions of biotic, geologic and geochemical processes. Humans have dramatically increased the concentration of **carbon** dioxide in the atmosphere over the last century through the burning of fossil **fuels** (**coal**, oil, and **natural gas**). As the concentration of **greenhouse gases**, like carbon dioxide and nitrous oxide, varies over many decades, so does the atmosphere's ability to capture and retain heat.

Other theories accounting for atmospheric cooling have been put forth. It has been suggested that **plate tectonics** are a significant factor affecting ice ages. The uplift of large continental blocks resulting from plate movements (for example, the uplift of the Himalayas and the Tibetan Plateau) may cause changes in global circulation patterns. The presence of large land masses at high altitudes seems to correlate with the growth of ice sheets, while the opening and closing of ocean basins due to tectonic movement may affect the movement of warm **water** from low to high latitudes.

Since **volcanic eruptions** can contribute to significant temperature variations, it has been suggested that such eruptions could contribute to atmospheric cooling, leading to the lowering of the earth's annual temperature. Dust particles thrown into the air during an eruption can reflect sunlight back into space, reducing heat that would otherwise have reached the earth's surface. The eruption of Mount Pinatubo in the Philippine Islands in 1991 is thought to have been responsible for a worldwide cooling that lasted for at least five years. Similarly, the earth's average annual temperature might be affected by the impact of meteorites on the earth's surface. If very large meteorites had struck the earth at times in the past, such collisions would have released huge volumes of dust into the atmosphere. The presence of this dust would have had effects similar to the eruption of Mount Pinatubo, reducing the earth's annual average temperature for an extended period of time and, perhaps, contributing to the development of an ice age.

The ability to absorb heat and the reflectivity of the earth's surface also contribute to changes in the annual average temperature of the earth. Once an ice age begins, sea levels drop as more and more water is tied up in ice sheets and glaciers. More land is exposed, and because land absorbs heat less readily than water, less heat is retained in the earth's atmosphere. Likewise, pale surfaces reflect more heat than dark surfaces, and as the **area** covered by ice increase, so does the amount of heat reflected back to the upper atmosphere.

Whatever the cause of ice ages, it is clear that they can develop as the result of relatively small changes in the earth's average annual temperature. It appears that annual variations of only a few degrees Celsius can result in the formation of extensive ice sheets that cover thousands of square miles of the earth's surface.

See also Earth (planet); Glacial landforms; Glaciation; Historical geology; Polar axis and tilt; Polar ice

ICE HEAVING AND WEDGING

Some 35% of Earth's land **area** undergoes regular **freezing** and thawing. **Ice** heaving and ice wedging are two of the mechanisms by which **water** in **soil** lifts, penetrates, and sorts soils and rocks when repeatedly melted and frozen. Ice heaving is the lifting of soil by horizontal ice layers; ice wedging is the top-down growth into soil of vertical wedges of ice.

Ice heaving is driven by complex molecular interactions between water and soil. The simple result of these complex interactions is that ice forming in soil sucks water to itself by capillary action. The suction exerted by ice upon water in soil is termed cryosuction. Since freezing normally proceeds from the surface down, ice heaving begins with the formation of a layer of ice near the surface. As it grows, this layer draws water to itself from below by cryosuction. This water freezes to the underside of the growing layer. The ice thus formed is termed segregation ice because it grows by segregating previously mixed soil and water. Segregation ice forms from water transported by cryosuction to the upper soil; this imported material, aided slightly by water's 9% expansion upon freezing, raises up the overlying ground surface as segregation ice forms, causing ice heaving.

Segregation ice often forms regularly spaced layers. As each layer forms, it tends to suck dry the soil beneath it. When the force of cryosuction is no longer able to lift water from below, thickening of the current layer ceases and cooling proceeds downward until a new ice layer can begin to form at a greater depth.

Ice wedges form by a simpler process. When soil cools it contracts; this contraction produces cracks. Water trickles into the cracks and freezes, forming an incipient ice wedge. Subsequent cycles of temperature-driven expansion and shrinkage cause the wedge to crack open repeatedly, admitting additional water each time. Wedge ice is termed intrusion ice because its water is not drawn from the surrounding soil, but intrudes into it.

Any flat, smooth coating of particles and liquid (e.g., mud, paint, or soil) tends to crack in a pattern of polygonal shapes when it shrinks, whether by cooling or drying. Large areas of far-northern land are, consequently, covered by ice-wedge polygons, often many meters across. These polygons are an example of patterned ground—that is, terrain marked by natural, repeating, geometric shapes. Most patterned ground is produced by cyclic freezing and thawing, whether by heaving, wedging, or other mechanisms.

Ice wedging is restricted to the far north and high-altitude areas. Ice heaving occurs wherever wet ground freezes even superficially. Pipkrakes—the crunchy, vertical-fibered ice **crystals** that spring up in wet soil on freezing nights—are a small-scale example of ice heaving.

See also Phase state changes

ICEBERGS

An iceberg is a large mass of free-floating **ice** that has broken away from a glacier. Beautiful and dangerous, icebergs wander over the ocean surface until they melt. Most icebergs come from the **glaciers** of Greenland or from the massive ice sheets of **Antarctica**. A few icebergs originate from smaller Alaskan glaciers. Snow produces the glaciers and ice sheets so, ultimately, icebergs originate from snow. In contrast, "sea ice" originates from **freezing** salt **water**. When fragments break off of a glacier, icebergs are formed in a process called calving.

Iceberg. ***Photograph by Commander Richard Behn, NOAA Corps. National Oceanic and Atmospheric Administration.***

Icebergs consist of **freshwater** ice, pieces of debris, and trapped bubbles of air. The combination of ice and air bubbles causes sunlight shining on the icebergs to refract, coloring the ice spectacular shades of blue, green, and white. Color may also indicate age; blue icebergs are old, and green ones contain algae and are young. Icebergs come in a variety of shapes and sizes, some long and flat, others towering and massive.

An iceberg floats because it is lighter and less dense than salty seawater, but only a small part of the iceberg is visible above the surface of the sea. Typically, about 80–90% of an iceberg is below sea level, so they drift with ocean currents rather than **wind**. Scientists who study icebergs classify true icebergs as pieces of ice that are greater than 16 ft (5 m) above sea level and wider than 98 ft (30 m) at the water line. Of course, icebergs may be much larger. Smaller pieces of floating ice are called “bergy bits” (3.3–16 ft or 1–5 m tall and 33–98 ft or 10–30 m wide) or “growlers” (less than 3.3 ft or 1 m tall and less than 33 ft or 10 m wide). The largest icebergs can be taller than 230 ft (70 m) and wider than 738 ft (225 m). Chunks of ice more massive than this are called ice islands. Ice islands are much more common in the Southern Hemisphere, where they break off the Antarctic ice sheets.

Because of the unusual forms they may take, icebergs are also classified by their shape. Flat icebergs are called tabular. Icebergs that are tall and flat are called blocky. Domed icebergs are shaped like a turtle shell, rounded, with gentle slopes. Drydock icebergs have been eroded by waves so that they are somewhat U-shaped. Perhaps the most spectacular are the pinnacle icebergs, which resemble mountain tops, with one or more central peaks reaching skyward.

The life span of an iceberg depends on its size but is typically about two years for icebergs in the Northern Hemisphere. Because they are larger, icebergs from Antarctica may last for several more years. Chief among the destructive forces that work against icebergs are wave action and heat. Wave action can break icebergs into smaller pieces and can cause icebergs to knock into each other and fracture. Relatively warm air and water **temperature** gradually melt the ice. Because icebergs float, they drift with water currents towards the equator into warmer water. Icebergs may drift as far as 8.5 mi (14 km) per day. Most icebergs have completely melted by the time they reach about 40 degrees **latitude** (north or south). There have been rare occasions when icebergs have drifted as far south as Bermuda (32 degrees north latitude), which is located about 900 mi (1,400 km) east of Charleston, South Carolina. In the Atlantic Ocean, they have also been found as far east as the Azores, islands in the Atlantic Ocean off the coast of Spain.

One of the best-known icebergs is the one that struck and sank the RMS *Titanic* on April 14, 1912, when the ship was on her maiden voyage. More than 1,500 people lost their lives in that disaster, which occurred near Newfoundland, Canada. As a result of the tragedy, the Coast Guard began monitoring icebergs to protect shipping interests in the North Atlantic sea lanes. Counts of icebergs drifting into the North Atlantic shipping lanes vary from year to year, with little predictability. During some years, no icebergs drift into the lanes; other years are marked by hundreds or more—as many as 1,572 have been counted in a single year. Many ships now carry their own radar equipment to detect icebergs. As recently as 1959, a Danish ship equipped with radar struck an iceberg and sank, resulting in 95 deaths. Some ships even rely on infrared sensors from airplanes and satellites. Sonar is also used to locate icebergs.

Modern iceberg research continues to focus on improving methods of tracking and monitoring icebergs, and on learning more about iceberg deterioration. In 1995, a huge iceberg broke free from the Larsen ice shelf in Antarctica. This iceberg was 48 mi (77 km) long, 23 mi (37 km) wide, and 600 ft (183 m) thick. The iceberg was approximately the size of the country of Luxembourg and isolated James Ross Island (one of Antarctica's islands) for the first time in recorded history. The megaberg was monitored by airplanes and satellites to make sure it didn't put ships at peril. According to some scientists, this highly unusual event could be evidence of **global warming**. Surges in the calving of icebergs known as Heinrich events are also known to be caused by irregular motions of Earth around the **Sun** that cause ocean waters of varying temperatures and salinity to change their circulation patterns. These cycles were common during the last glacial period, and glacial debris was carried by "iceberg armadas" to locations like Florida and the coast of Chile. Scientists have "captured" icebergs for study including crushing to measure their strength. It has been proposed to tow icebergs to drought-stricken regions of the world to solve water shortage problems; however, the cost and potential environmental impact of such an undertaking have so far discouraged any such attempts.

See also Glaciation; Ocean circulation and currents

IGNEOUS ROCKS

The first rocks on Earth were igneous rocks. Igneous rocks are formed by the cooling and hardening of molten material called **magma**. The word igneous comes from the Latin word *ignis*, meaning fire. There are two types of igneous rocks: intrusive and extrusive. Intrusive igneous rocks form within Earth's **crust**; the molten material rises, filling any available crevices, into the crust, and eventually hardens. These rocks are not visible until the earth above them has eroded away. Intrusive rocks are also called plutonic rocks, named after the Greek god Pluto, god of the underworld. A good example of intrusive igneous **rock** is **granite**. Extrusive igneous rocks form when the magma or molten rock pours out onto the earth's surface or erupts at the earth's surface from a **volcano**. Extrusive rocks are also called volcanic rocks. **Basalt**, formed from hardened **lava**, is the most common extrusive rock. **Obsidian**, a black glassy rock, is also an extrusive rock.

Igneous rocks are classified according to their texture and mineral or chemical content. The texture of the rock is determined by the rate of cooling. The slower the cooling, the larger the crystal. Intrusive rock can take one million years or more to cool. Fast cooling results in smaller, often microscopic, grains. Some extrusive rocks solidify in the air, before they hit the ground. Sometimes the rock mass starts to cool slowly, forming larger **crystals**, and then finishes cooling rapidly, resulting in rocks that have crystals surrounded by a fine, grainy rock mass. This is known as a porphyritic texture.

Most of Earth's **minerals** are made up of a combination of up to ten elements. Over 99% of Earth's crust consists of only eight elements (**oxygen**, **silicon**, **aluminum**, **iron**, calcium, sodium, potassium, and magnesium). Most igneous rocks contain two or more minerals, which is why some rocks have more than one color. For example, the most common minerals in granite are **quartz** (white or gray), **feldspar** (white or pinks of varying shades), and mica (black). The amount of a specific element in a mineral can determine a color or intensity of color. Because of the way granite is formed, the different composition of minerals is easy to see. It is difficult to see the distinct composition of some extrusive rocks, like obsidian, due to their extremely fine texture. Igneous rocks contain mostly silicate minerals and are sometimes classified according to their silica content. Silica (SiO_2) is a white or colorless mineral compound. Rocks containing a high amount of silica, usually more than 50%, are considered acidic (sometimes the term **felsic** is used), and those with a low amount of silica are considered basic (or **mafic**). Acidic rocks are light in color and basic rocks are dark in color.

Essentially, Earth's continents are slabs of granite sitting on top of molten rock. The crustal plates of Earth are continually shifting, being torn open by faults, and altered by earthquakes and volcanoes. New igneous material is continually added to the crust, while old crust falls back into the earth, sometimes deep enough to be remelted. Igneous rocks are the source of many important minerals, **metals**, and building materials.

See also Magma chamber; Volcanic eruptions

IMPACT CRATER

An impact crater is a physical scar on a planetary body's surface (topographic depression or geological structure) that is the result of hypervelocity impact by a minor planet, such as an asteroid, comet, or meteorite. Most impact craters are generally circular, although elliptical impact craters are known from very low-angle or obliquely impacting projectiles. In addition, some impact craters have been tectonically deformed and thus are no longer circular. Impact craters may be exposed, buried, or partially buried. Geologists distinguish an impact crater, which is rather easily seen, from an impact structure, which is an impact crater that may be in a state of poor preservation. A meteorite crater is distinguished from other impact craters because there are fragments of the impacting body preserved near the crater. Typically, a meteorite crater is a rather small feature under 0.6 mi (1 km) in diameter.

The impact crater is the most common landform on the surface of most of the rocky and icy planets and satellites in our **solar system**. Impact craters are obliterated or covered over by younger materials where re-surfacing rates are high (e.g., Venus and Io) and where **weathering** and **erosion** are intensive (e.g., Earth and parts of Mars). At present, there are about 150 to 200 impact craters and impact structures on Earth that have been scrutinized sufficiently to prove their origin. There are several hundred other possible impact features that also have been identified. Given Earth's rather rapid weathering and tectonic cycling of **crust**, this is a relatively large preserved crater record. Even though preserved craters are rare on Earth, there is no reason to suspect that Earth has been bombarded any less intensively than the **Moon**, and thus, the vast majority of Earth's impact features must have been erased.

Impact craters are subdivided into three distinctive morphologic classes, which are related to crater size. The simple impact crater is a bowl-shaped feature with relatively high depth to diameter ratio. Most simple impact craters on Earth are less than 1.2 mi (2 km) in diameter. The complex impact crater has a low depth to diameter ratio and possesses a central uplift and a down-faulted and terraced rim structure. Some large complex impact craters possess an uplifted inner ring structure rather than a simple central uplift and they have a down-faulted and terraced rim as well. Complex impact craters on Earth range from the upper limit of simple impact craters to approximately 62 mi (100 km) in diameter. Multi-ring craters (also called multi-ring basins) are impact craters with depth to diameter ratios like complex impact craters, but they possess at least two outer, concentric rings (marked by normal faults with downward motion toward crater center). The five multi-ring impact craters known on Earth range from 62–124 mi (100–200 km) in diameter. On the Moon and other planets and satellites in the solar system, the range of multi-ring crater diameters is from several hundred miles up to 2,485 mi (4,000 km) in diameter. A planet or satellite's **gravity** and the strength of the surface material determine the transition diameter from simple to complex and complex to multi-ring impact crater morphology.

Impact craters go through three stages during formation. Contact and compression is the initial stage. Contact occurs when the projectile first touches the planet's or satellite's surface. Jetting of molten material from the planet's upper crust can occur at this stage and initial penetration of the crust begins. During compression, the projectile is compressed as it enters the target crustal material. Depending upon relative strength of the target and projectile, the projectile usually penetrates only a few times its diameter into the crust. The average velocity of a cosmic projectile is approximately 12.4 mi/sec (20 km/sec) and nearly all the vast kinetic energy of this projectile is imparted to the surrounding crust as shock wave energy. This huge shock wave propagates outward radially into the crust from the point of projectile entry. At the end of compression, which lasts a tiny fraction of a second to two seconds at most (depends upon projectile size), the projectile is vaporized by a shock wave that bounces from the front of the projectile to the back and then forward. At this point, the projectile itself is no longer a factor in what happens subsequently. The subsequent excavation stage is driven by the shock wave propagating through the surrounding target crust. The expanding shock wave moves material along curved paths, thus ejecting debris from the opening crater cavity. This is the origin of the transient crater cavity. It may take several seconds to a few minutes to open this transient crater cavity, depending upon the kinetic energy imparted by the projectile. Material cast out of the opening crater during this phase forms an ejecta curtain that extends high above the impact **area**. This ejected material will fall back, thus forming an ejecta blanket in and around the impact crater. During the final modification stage, gravity takes over and causes crater-rim collapse in simple impact craters. In complex and multi-ring impact craters, there is central peak or peak-ring uplift and coincident gravitational collapse in the rim area. Lingering effects of the modification stage may go on for many years after impact.

There is a general relationship between impact-crater diameter, approximate projectile diameter, energy released (in joules (J) and megatons of TNT (MT)). Generally, the ratio 20:1 relates crater diameter to projectile diameter. Kinetic energy imparted to the target may be computed using the formula $KE = \frac{1}{2} mv^2$, where m is projectile mass and v is its velocity.

Further, observational data for **asteroids** and **comets** give us a general idea of impact frequency (n/10^6 years), and mean interval between such impacts for projectiles of given sizes. All this can be combined to give scientists an idea of the magnitude of impact energy release and how often it occurs. For example, a .62 mi (1 km) diameter impact crater would be made by a projectile 165 ft (50 m) in diameter, which would release approximately 4.6 x 10^{16} J (= 11 MT) of energy upon impact. Such an impact would occur approximately 640 times per million (10^6) years, or on average about once per 1,600 years. For a 3.1 mi (5 km) diameter impact crater, an 820 ft (250 m) diameter projectile is required. Approximately 5.7 x 10^{18} J (= 1,400 MT) energy is released in such an event, which would occur approximately 35 times per million years (or once per 28,500 years on average). For a 6.2 mi (10 km) diameter impact crater, a 1,640 ft (500 m) diameter projectile is needed. Approximately 4.6 x 10^{19} J (= 11,000 MT) of energy would be released. Scientists expect that such events happen approximately 10 times per million years (or on average once per 100,000 years). For a 31 mi (50 km) diameter crater (made by a 1.6 mi (2.5 km) diameter projectile), we can expect a 5.8 x 10^{21} J (= 1.3 x 10^6 MT) energy release. This would happen approximately 0.22 times per million years or on average once per 4.5 million years. For a 62 mi (100 km) diameter crater (made by a 3.1 mi (5 km) diameter projectile), we can expect a 4.6 x 10^{22} J (= 1.1 x 10^7 MT) energy release. This would happen approximately 0.04 times per million years, or on average once per 26 million years. To put the energy release in perspective, the largest nuclear weapon ever tested on Earth yielded 58 MT. If all nuclear weapons that existed at the height of the Cold War were exploded at once, the yield would be approximately 10^5 MT. The impact event linked to the dinosaur extinction (Chicxulub impact structure, Mexico) has a diameter of nearly 124 mi (200 km).

It is thought that impact events related to craters greater than 62 mi (100 km) in diameter likely had globally devastating effects. These effects, which may have led to global ecosystem instability or collapse, included: gas and dust discharge into the upper atmosphere (blocking sunlight and causing greenhouse effects); heating of the atmosphere due to reentry of ballistic ejecta (causing extensive wildfires); seismic sea waves (causing tsunamis); and acid-rain production (causing damage to soils and **oceans**). There is much research currently underway to find the effect of cosmic impact events upon life on Earth during the geological past.

See also Asteroids; Barringer meteor crater; Comets; K-T event; Meteoroids and meteorites; Shock metamorphism

INDIAN OCEAN • *see* OCEANS AND SEAS

INDUSTRIAL MINERALS

Industrial **minerals** is a term used to describe naturally occurring non-metallic minerals that are used extensively in a variety of industrial operations. Some of the minerals commonly included in this category include asbestos, barite, boron compounds, clays, corundum, **feldspar**, fluorspar, phosphates, potassium salts, sodium chloride, and sulfur. Some of the mineral mixtures often considered as industrial minerals include construction materials such as **sand**, gravel, **limestone**, **dolomite**, and crushed **rock**; abrasives and refractories; **gemstones**; and lightweight aggregates.

Asbestos is a generic term used for a large group of minerals with complex chemical composition that includes magnesium, **silicon**, **oxygen**, hydrogen, and other elements. The minerals collectively known as asbestos are often sub-divided into two smaller groups, the serpentines and amphiboles. All forms of asbestos are best known for an important common property—their resistance to heat and flame. That property is responsible, in fact, for the name *asbestos* (Greek), meaning unquenchable. Asbestos has been used for thousands of years in the production of heat resistant materials such as lamp wicks.

Today, asbestos is used as a reinforcing material in cement, in vinyl floor tiles, in fire-fighting garments and fireproofing materials, in the manufacture of brake linings and clutch facings, for electrical and heat insulation, and in pressure pipes and ducts.

Prolonged exposure to asbestos fibers can block the respiratory system and lead to the development of asbestosis and/or lung cancer. The latency period for these disorders is at least 20 years, so men and women who mined the mineral or used it for various construction purposes during the 1940s and 1950s were not aware of their risk for these diseases until late in their lives. Today, uses of the mineral in which humans are likely to be exposed to its fibers have largely been discontinued.

Barite is the name given to a naturally occurring form of barium sulfate, commonly found in Canada, Mexico, and the states of Arkansas, Georgia, Missouri, and Nevada. One of the most important uses of barite is in the production of heavy muds that are used in drilling oil and gas wells. It is also used in the manufacture of a number of other commercially important industrial products such as paper coatings, battery plates, paints, linoleum and oilcloth, plastics, lithographic inks, and as filler in some kinds of textiles. Barium compounds are also widely used in medicine to provide the opacity that is needed in taking certain kinds of x rays.

Boron is a non-metallic element obtained most commonly from naturally occurring minerals known as borates. The borates contain oxygen, hydrogen, sodium, and other elements in addition to boron. Probably the most familiar boron-containing mineral is borax, mined extensively in salt **lakes** and alkaline soils.

Borax was known in the ancient world and used to make glazes and hard **glass**. Today, it is still an important ingredient of glassy products that include heat-resistant glass (Pyrex), glass wool and glass fiber, enamels, and other kinds of ceramic materials. Elementary boron also has a number of interesting uses. For example, it is used in nuclear reactors to absorb excess neutrons, in the manufacture of special-purpose alloys, in the production of semiconductors, and as a component or rocket propellants.

Corundum is a naturally occurring form of **aluminum** oxide that is found abundantly in Greece and Turkey and in New York State. It is a very hard mineral with a high **melting** point. It is relatively inert chemically and does not conduct an electrical current very well.

These properties make corundum highly desirable as a refractory (a substance capable of withstanding very high temperatures) and as an abrasive (a material used for cutting, grinding, and polishing other materials). One of the more mundane uses of corundum is in the preparation of toothpaste, where its abrasive properties help in keeping teeth clean and white.

In its granular form, corundum is known as emery. Many consumers are familiar with emery boards used for filing fingernails. Emery, like corundum, is also used in the manufacture of cutting, grinding, and polishing wheels.

The feldspars are a class of minerals known as the aluminum silicates. That is, they all contain aluminum, silicon, and oxygen, as sodium, potassium, and calcium. In many cases, the name feldspar is reserved for the potassium aluminum silicates. The most important commercial use of feldspar is in the manufacture of pottery, enamel, glass, and ceramic materials. The hardness of the mineral also makes it desirable as an abrasive.

Fluorspar is a form of calcium fluoride that occurs naturally in many parts of the world including **North America**, Mexico, and **Europe**. The compound gets its name from one of its oldest uses, as a flux. In Latin, the word *fluor* means flux. A flux is a material that is used in industry to assist in the mixing of other materials or to prevent the formation of oxides during the refining of a metal. For example, fluorspar is often added to an open-hearth steel furnace to react with any oxides that might form during that process. The mineral is also used during the smelting of an ore (the removal of a metal from its naturally occurring ore).

Fluorspar is also the principal source of fluorine gas. The mineral is first converted to hydrogen fluoride which, in turn, is then converted to the element fluorine. Some other uses of fluorspar are in the manufacture of paints and certain types of cement, in the production of emery wheels and **car-**

bon electrodes, and as a raw material for phosphors (a substance that glows when bombarded with energy, such as the materials used in color television screens).

The term phosphate refers to any chemical compound containing a characteristic grouping of atoms, given by the formula PO_4, or comparable groupings. In the field of industrial minerals, the term most commonly refers to a specific naturally occurring phosphate, calcium phosphate, or phosphate rock. By far the most important use of phosphate rock is in agriculture, where it is treated to produce fertilizers and animal feeds. Typically, about 80% of all the phosphate rock used in the United States goes to one of these agricultural applications.

Phosphate rock is also an important source for the production of other phosphate compounds, such as sodium, potassium, and ammonium phosphate. Each of these compounds, in turn, has a very large variety of uses in everyday life. For example, one form of sodium phosphate is a common ingredient in dishwashing detergents. Another, ammonium phosphate, is used to treat cloth to make it fire retardant. Potassium phosphate is used in the preparation of baking powder.

As with other industrial minerals mentioned here, the term potassium salts applies to a large group of compounds, rather than one single compound. Potassium chloride, sulfate, and nitrate are only three of the most common potassium salts used in industry. The first of these, known as sylvite, can be obtained from salt **water** or from fossil salt beds. It makes up roughly 1% of each deposit, the remainder of the deposit being sodium chloride (halite).

Potassium salts are similar to phosphate rocks in that their primary use is in agriculture, where they are made into fertilizers, and in the chemical industry, where they are converted into other compounds of potassium. Some compounds of potassium have particularly interesting uses. Potassium nitrate, for example, is unstable and is used in the manufacture of explosives, fireworks, and matches.

Like potassium chloride, sodium chloride (halite) is found both in sea water and in underground salt mines left as the result of the **evaporation** of ancient **seas**. Sodium chloride has been known to and used by humans for thousands of years and is best known by its common name of salt, or table salt. By far its most important use is in the manufacture of other industrial chemicals, including sodium hydroxide, hydrochloric acid, chlorine, and metallic sodium. In addition, sodium chloride has many industrial and commercial uses. Among these are in the preservation of foods (by salting, pickling, corning, curing, or some other method), highway de-icing, as an additive for human and other animal foods, in the manufacture of glazes for ceramics, in water softening, and in the manufacture of rubber, **metals**, textiles, and other commercial products.

Sulfur occurs in its elementary form in large underground deposits from which it is obtained by traditional mining processes or, more commonly, by the Frasch process. In the Frasch process, superheated water is forced down a pipe that has been sunk into a sulfur deposit. The heated water melts the sulfur, which is then forced up a second pipe to the earth's surface.

The vast majority of sulfur is used to manufacture a single compound, sulfuric acid. Sulfuric acid consistently ranks number one in the United States as the chemical produced in largest quantity. Sulfuric acid has a very large number of uses, including the manufacture of fertilizers, the refining of **petroleum**, the pickling of steel (the removal of oxides from the metal's surface), and the preparation of detergents, explosives, and synthetic fibers.

A significant amount of sulfur is also used to produce sulfur dioxide gas (actually an intermediary in the manufacture of sulfuric acid). Sulfur dioxide, in turn, is extensively used in the pulp and paper industry, as a refrigerant, and in the purification of sugar and the bleaching of paper and other products. Some sulfur is refined after being mined and then used in its elemental form. This sulfur finds application in the vulcanization of rubber, as an insecticide or fungicide, and in the preparation of various chemicals and pharmaceuticals.

See also Geochemistry; Petroleum, economic uses of

INNER CORE • *see* EARTH, INTERIOR STRUCTURE

INOSILICATES

The most abundant rock-forming **minerals** in the **crust** of the earth are the silicates. They are formed primarily of **silicon** and **oxygen**, together with various **metals**. The fundamental unit of these minerals is the silicon-oxygen tetrahedron. These tetrahedra have a pyramidal shape, with a relatively small silicon cation (Si^{+4}) in the center and four larger oxygen anions (O^{-2}) at the corners, producing a net charge of –4. **Aluminum** cations (Al^{+3}) may substitute for silicon, and various anions such as hydroxyl (OH^-) or fluorine (F^-) may substitute for oxygen. In order to form stable minerals, the charges that exist between tetrahedra must be neutralized. This can be accomplished by the sharing of oxygen atoms between tetrahedra, or by the binding together adjacent tetrahedra by various metal cations. This in turn creates characteristic silicate structures that can be used to classify silicate minerals into **cyclosilicates**, inosilicates, **nesosilicates**, **phyllosilicates**, **sorosilicates**, and **tectosilicates**.

Minerals where the silicon-oxygen tetrahedra form chains are called inosilicates. They can take the form of single chains, where tetrahedra line up single-file through the sharing of oxygen atoms, or they can form double chains where the tetrahedra of adjacent single chains also share oxygen atoms. Two important groups of insosilicates are the pyroxenes and the amphiboles. Minerals of the pyroxene group are single-chain ferromagnesian silicates; examples of pyroxene group minerals include enstatite ($MgSiO_3$) and jadeite ($NaAlSi_2O_6$). Minerals of the amphibole group are double-chain ferromagnesian silicates; examples of amphibole group minerals include grunerite ($Fe_7Si_8O_{22}(OH)_2$) and tremolite ($Ca_2Mg_5Si_8O_{22}(OH)_2$). The same cations (such as calcium and sodium) are present in both groups, but the hydroxyl anion is characteristic of amphiboles.

Both pyroxenes and amphiboles are important rock-forming minerals in igneous and metamorphic rocks.

See also Chemical bonds and physical properties

INSOLATION AND TOTAL SOLAR IRRADIANCE

Total solar irradiance is defined as the amount of radiant energy emitted by the **Sun** over all wavelengths that fall each second on 11 ft^2 (1 m^2) outside Earth's atmosphere. Insolation is the amount of **solar energy** that strikes a given **area** over a specific time, and varies with **latitude** or the **seasons**.

By way of further definition, irradiance is defined as the amount of electromagnetic energy incident on a surface per unit time per unit area. Solar refers to electromagnetic radiation in the spectral range of approximately 1–9 ft (0.3–3 m), where the shortest wavelengths are in the ultraviolet region of the spectrum, the intermediate wavelengths in the visible region, and the longer wavelengths are in the near infrared. Total solar irradiance means that the solar flux has been integrated over all wavelengths to include the contributions from ultraviolet, visible, and infrared radiation.

By convention, the surface features of the Sun are classified into three regions: the photosphere, the chromosphere, and the corona. The photosphere corresponds to the bright region normally visible to the naked eye. About 3,100 mi (5,000 km) above the photosphere lies the chromosphere, from which short-lived, needle-like projections may extend upward for several thousands of kilometers. The corona is the outermost layer of the Sun; this region extends into the region of the planets. Most of the surface features of the Sun lie within the photosphere, though a few extend into the chromosphere or even the corona.

The average amount of energy from the Sun per unit area that reaches the upper regions of Earth's atmosphere is known as the solar constant; its value is approximately 1,367 watts per square meter. As Earth-based measurements of this quantity are of doubtful accuracy due to variations in Earth's atmosphere, scientists have come to rely on satellites to make these measurements.

Although referred to as the solar constant, this quantity actually has been found to vary since careful measurements started being made in 1978. In 1980, a satellite-based measurement yielded the value of 1,368.2 watts per square meter. Over the next few years, the value was found to decrease by about 0.04% per year. Such variations have now been linked to several physical processes known to occur in the Sun's interior, as will be described below.

From Earth, it is only possible to observe the radiant energy emitted by the Sun in the direction of our planet; this quantity is referred to as the solar irradiance. This radiant solar energy is known to influence Earth's **weather and climate**, although the exact relationships between solar irradiance and long-term climatological changes, such as **global warming**, are not well understood.

The total radiant energy emitted from the Sun in all directions is a quantity known as solar luminosity. The luminosity of the Sun has been estimated to be 3.8478 x 10^{26} watts. Some scientists believe that long-term variations in the solar luminosity may be a better correlate to environmental conditions on Earth than solar irradiance, including global warming. Variations in solar luminosity are also of interest to scientists who wish to gain a better understanding of stellar **rotation**, convection, and **magnetism**.

Because short-term variations of certain regions of the solar spectrum may not accurately reflect changes in the true luminosity of the Sun, measurements of total solar irradiance, which by definition take into account the solar flux contributions over all wavelengths, provide a better representation of the total luminosity of the Sun.

Short-term variations in solar irradiation vary significantly with the position of the observer, so such variations may not provide a very accurate picture of changes in the solar luminosity. But the total solar irradiance at any given position gives a better representation because it includes contributions over the spectrum of wavelengths represented in the solar radiation.

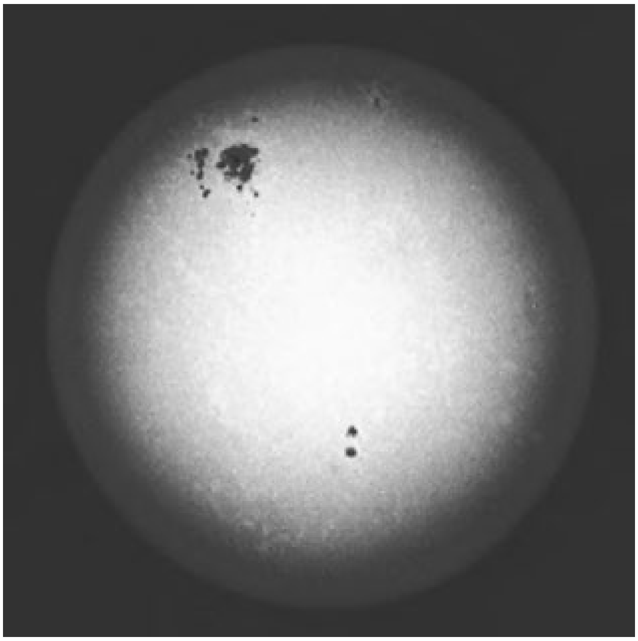
Variations in the solar irradiance are at a level that can be detected by ground-based astronomical measurements of light. Such variations have been found to be about 0.1% of the average solar irradiance. Starting in 1978, space-based instruments aboard the *Nimbus 7* Solar Maximum Mission, and other satellites began making the sort of measurements (reproducible to within a few parts per million each year) that allowed scientists to acquire a better understanding of variations in the total solar irradiance.

Variations in solar irradiance have been attributed to the following solar phenomena: Oscillations, granulation, sunspots, faculae, and solar cycle.

Oscillations, which cause variations in the solar irradiance lasting about five minutes, arise from the action of resonant waves trapped in the Sun's interior. At any given time, there are tens of millions of frequencies represented by the resonant waves, but only certain oscillations contribute to variations in the solar constant.

Granulation, which produces solar irradiance variations lasting about 10 minutes, is closely related to the convective energy flow in the outer part of the Sun's interior. To the observer on Earth, the surface of the Sun appears to be made up of finely divided regions known as granules, each from 311—1,864 mi (500–3,000 km) across, separated by dark regions. Each of these granules makes its appearance for about 10 minutes and then disappears. Granulation apparently results from convection effects that appear to cease several hundred kilometers below the visible surface, but in fact extend out into the photosphere, i.e., the region of the Sun visible to the naked eye. These granules are believed to be the centers of rising convection cells.

Sunspots give rise to variations that may last for several days, and sometimes as long as 200 days. They actually correspond to regions of intense magnetic activity where the solar atmosphere is slightly cooler than the surroundings. Sunspots



Visible light image of the Sun, showing sunspots. *U.S. National Aeronautics and Space Administration (NASA).*

appear as dark regions on the Sun's surface to observers on Earth. They are formed when the **magnetic field** lines just below the Sun's surface become twisted, and then poke though the solar photosphere. Solar irradiance measurements have also shown that the presence of large groups of sunspots on the Sun's surface produce dips ranging in amplitude from 0.1 to 0.25% of the solar constant. This reduction in the total solar irradiance has been attributed both to the presence of these sunspots and to the temporary storage of solar energy over times longer than the sunspot's lifetime. Another key observation has been that the largest decreases in total solar irradiance frequently coincide with the formation of newly formed active regions associated with large sunspots, or with rapidly evolving, complex sunspots. Sunspots are especially noteworthy for their 11-year activity cycle.

Faculae, producing variations that may last for tens of days, are bright regions in the photosphere where high-temperature interior regions of the Sun radiate energy. They tend to congregate in bright regions near sunspots, forming solar active regions. Faculae, which have sizes on the order of 620 mi (1,000 km) or less, appear to be tube-like regions defined by magnetic field lines. These regions are less dense than surrounding areas. Because radiation from hotter layers below the photosphere can leak through the walls of the faculae, an atmosphere is produced that appears hotter, and brighter, than others.

The solar cycle is responsible for variations in the solar irradiance that have a period of about 11 years. This 11-year activity cycle of sunspot frequency is actually half of a 22-year magnetic cycle, which arises from the reversal of the poles of the Sun's magnetic field. From one activity cycle to the next, the north magnetic pole becomes the south magnetic pole, and vice versa. Solar luminosity has been found to achieve a maximum value at the very time that sunspot activity is highest during the 11-year sunspot cycle. Scientists have confirmed the length of the solar cycle by examining tree rings for variations in deuterium-to-hydrogen ratios. This ratio is temperature-dependent because deuterium molecules, which are a heavy form of the hydrogen molecule, are less mobile than the lighter hydrogen molecules, and therefore less responsive to thermal motion induced by increases in the solar irradiance.

Surprisingly, the Sun's rotation, with a rotational period of about 27 days, does not give rise to significant variations in the total solar irradiance. This is because its effects are overridden by the contributions of sunspots and faculae.

Scientists have speculated that long-term solar irradiance variations might contribute to global warming over decades or hundreds of years. More recently, there has been speculation that changes in total solar irradiation have amplified the **greenhouse effect**, i.e., the retention of solar radiation and gradual warming of Earth's atmosphere. Some of these changes, particularly small shifts in the length of the activity cycle, seem to correlate rather closely with climatic conditions in pre- and post industrial times. Whether variations in solar irradiance can account for a substantial fraction of global warming over the past 150 years, however, remains a highly controversial point of discussion.

See also Electromagnetic spectrum; Greenhouse gases and greenhouse effect; Solar energy; Solar illumination: Seasonal and diurnal patterns

INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS WORLD DATA CENTER

The International Council of Scientific Unions (ICSU) is a non-governmental organization, founded in 1931, to bring together natural scientists in international scientific endeavor. It comprises multi-disciplinary national scientific members (scientific research councils or science academies) and international, single-discipline scientific unions to provide a wide spectrum of scientific expertise enabling members to address major international, interdisciplinary issues which none could handle alone.

In 1952, the ICSU proposed a comprehensive series of global geophysical activities to span the period July 1957 to December 1958. The International Geophysical Year (IGY), as it was called, was modeled on the International Polar Years of 1882–83 and 1932–33, and was intended to allow scientists from around the world to take part in a series of coordinated observations of various phenomena in Geophysics. A special committee, CSAGI (Comité Spécial de l'Année Géophysique Internationale), was formed to act as the governing body for all IGY activities. Among them, CSAGI established a World Data Center (WDC) system to serve the IGY, and developed data management plans for each IGY's scientific discipline. The data specifications were published in a series of *Guides to*

Data Exchange, originally issued in 1957, and consecutively updated. Data sets were prepared in machine-readable form, which at that time meant punched cards and punched tape. Because of its success, the WDC system was declared permanent at the 22nd General Assembly of ICSU (Beijing, 1988). Since 1999, WDCs are referenced by the type of center rather that by the country operating the center, as for example the World Data Center for Marine Environmental Studies (WDC-MARE at Bremen University, Germany). All centers now have computer facilities and most use electronic networks to meet requests, exchange describing meta-information, and transfer data.

The basic principles and responsibilities include that World Data Centers are operated by national organizations for the benefit of the international scientific community. The resources required to operate WDCs are the responsibility of the host country or institution, which is expected to provide these resources on a long-term basis. If for any reason a WDC is closed, the data holdings shall be transferred to another center. WDCs receive data from individual scientists, projects, institutions, and local and national data centers. Among others, the mechanisms for data acquisition include the WDC Panel's "data rescue" program, which involves all parts of the WDC system and has two main aspects: (1) safeguarding older data sets that may be at risk of loss or deterioration; (2) digitizing old data sets to enable modern techniques to be used for their analysis. WDCs exchange data among themselves, as mutually agreed and whenever possible without charge, to facilitate data availability, to provide back-up copies, and to aid the preparation of higher order data products. They compile specialized data sets for small-scale, regional and global research and combine data from various sources to derive data products, such as indices of solar activity.

WDCs will provide data to scientists in any country free of charge, on an exchange basis or at a cost not to exceed the cost of copying and sending the requested data. Data sets are made available online through the World Wide Web or on media as CD-ROM, enabling users to search large data collections and transfer them to their home laboratory.

Data may be subject to privileged use by their principal investigators, for a period to be agreed beforehand, and not to surpass two years from the date of acquisition by the WDC. Since unpublished data are even more sensitive than published data, the WDC ensures that data be not accessed until they are formally placed in the public domain. In any case, data policy requires the acknowledgement of the original data sources in order to protect the principal investigator.

See also Scientific data management in Earth Sciences

INTERNATIONAL SPACE STATION (ISS)

The International Space Station (ISS) is the most complex international aerospace project in history. Sixteen countries contribute to this massive structure that measures 360 ft (110 m) wide and 289 ft (88 m) long. At Earth's surface **gravity**, the ISS would weigh 503 tons (456,620 kg). Constructed from specialized component modules, the ISS is designed to allow humans to live in space for long durations of time and provide a laboratory for both scientific and engineering experiments. The modular design allows sections to be completed and tested on Earth before being booted into orbit. In addition, the modular design provides a level of security to ISS personnel. Damage from a failure or rupture of a component module can be isolated and the crew evacuated to safe modules. Modular designs are also economical because they allow rapid adaptation to the station to specific uses without having to subject the station to extensive retrofitting. In a engineering sense, the modular design allows maximum safety, design flexibility, and use adaptation at the lowest cost.

Long-range plans include use of the ISS as a spaceport where spacecraft can dock to transfer people, cargo, and fuel without having to re-enter Earth's atmosphere. Use of the ISS as a spaceport would thus, facilitate the construction of a fleet of true space vehicles—craft designed to operate exclusively outside Earth's atmosphere. Such craft would not need to be constructed to withstand the dynamic pressures of reentry, nor would their engine systems need to be designed to provide thrust capable of propelling the craft to high escape velocities.

Although the United States and Russia shoulder the bulk of the technological burden of ISS design and orbital placement, other nations, including Canada, Japan, the 11 nations of the European Space Agency (ESA) and Brazil significantly contribute to ISS development.

The United States is responsible for constructing and operating major ISS elements and systems. The U.S. systems include thermal control, life support, guidance, navigation and control, data handling, power systems, communications and tracking, ground operations facilities, and launch-site processing facilities. Canada is providing a 55-foot-long (16.8 m) robotic arm to be used for the station's assembly and maintenance. The European Space Agency is contributing a pressurized laboratory to be launched on the **Space Shuttle**, and logistics transport vehicles to be launched on an ESA *Ariane 5* launch vehicle. Japan is providing a laboratory to be used for experiments and logistics transport vehicles. Russia is contributing two research modules, the Service Module, which includes early living quarters with life support and habitation systems, a science power platform that can supply 20 kilowatts of electrical power, logistics transport vehicles, and Soyuz spacecraft for crew drop off and pick up. Through agreement with the United States, Italy, and Brazil are also providing ISS components and laboratory research facilities.

Approved by President Ronald Reagan in 1984, ISS (then designated Space Station *Freedom*) development was put on hold by the turmoil and collapse of the Soviet Union in the late 1980s and the subsequent emergence of a revitalized Russian Space Agency in 1993. Broadened in scope to include a true international collaboration, in November of 1998, Russia launched the first part of the developing space station. More than four times as large as the Russian *Mir* space station, ISS assembly will continue until at least 2004.

ISS orbits at an altitude of 250 statute miles with an inclination of 51.6 degrees. This orbit allows maximum accessibility to the station for docking, crew **rotation**, and supply delivery. The orbit also allows for excellent observation of Earth. Orbital dynamics allow observation of up to 85% of Earth's surface and overflight of approximately 95% of Earth's heavily populated areas. Accordingly, the ISS is an ideal platform for the study of dynamic Earth geophysical processes and the long term study of the effects human civilization has upon both the physical and ecological landscape.

In addition to astronomical and **Earth science** research groups, the ISS will support medical and industrial research (e.g., the formation of certain alloys and **crystals** in low gravity environments).

See also History of manned space exploration; Space and planetary geology; Space physiology; Space probe; Spacecraft, manned

INTRUSIVE COOLING

Igneous rocks formed below ground level are termed intrusive, meaning that they originate as **magma** (liquid **rock**) that has intruded itself into preexisting solid rock by squeezing into cracks, eating its way upward from the mantle, or by other means. An intrusive magmatic body begins to cool as soon as it is emplaced, and as it cools, it crystallizes into a mixed mass of mineral grains. Which **minerals** form depends in a complex way on the exact ingredients of the magma and on the speed at which it is cooled. In general, slow cooling permits larger **crystals** to form while fast cooling produces smaller crystals.

Cooling is affected by shape and other factors. Thin or narrow bodies cool faster than globular ones; small bodies cool faster than large ones; convecting bodies cool faster than static (nonconvecting) ones; and bodies surrounded by relatively low-temperature rock cool faster than those emplaced in warm environments. By human standards, cooling time for intruded magma may be quite long. A horizontal, sheet-shaped intrusion of 1,562°F (850°C) magma 2,300 ft (701 m) thick, intruded beneath a cool 77–122°F (25–50°C) cover of rock half as thick, takes 9,000 years to completely crystallize. A vertical sheet of 1,472°F (800°C) magma 6,560 ft (2,000 m) thick emplaced in 212°F (100°C) rock takes 64,000 years to crystallize all through. The largest magmatic intrusions may take a million years to crystallize.

Near-surface intrusive cooling may be speeded by convection of **groundwater** through surrounding rock. In this case, **water** may transport minerals toward and away from the cooling intrusion, further complicating the process of mineral formation.

See also Batholith; Bowen's reaction series; Extrusive cooling; Pluton and plutonic bodies

IONIC BONDS • *see* CHEMICAL BONDS AND PHYSICAL PROPERTIES

IONOSPHERE

The ionosphere is a layer of the earth's atmosphere that is weakly ionized, and thus conducts **electricity**. It is located approximately in the same region as the top half of the **mesosphere** and the entire **thermosphere** in the upper atmosphere, from about 40 mi (60 km), continuing upward to the magnetosphere.

In the ionosphere, the molecules and atoms in the air are ionized mostly by the Sun's ultraviolet, x-ray, and corpuscular radiation, and partially by cosmic rays, resulting in ions and free electrons. The ionization process depends on many factors such as the Sun's activity (e.g., sunspot cycles), time (e.g., seasonal or daily changes), or geographical location (different at polar regions, mid-latitudes or equatorial zones).

The ionosphere can be further divided into sub-regions according to their free electron density profile that indicates the degree of ionization, and these sub-regions are called the D, E, and F layers. The D layer is located lowest among them, and it does not have an exact starting point. It absorbs high-frequency radio waves, and exists mainly during the day. It weakens, then gradually even disappears at night, allowing radio waves to penetrate into a higher level of the ionosphere, where these waves are reflected back to Earth, then bounce again back into the ionosphere. This explains why AM radio signals from distant stations can easily be picked up at night, even from hundreds of miles. Above the D layer, the E layer (or Kennelly-Heaviside layer) can be found, which historically was the first one that was discovered. After sunset, it usually starts to weaken and by night, it also disappears. The E layer absorbs x rays, and it has its peak at about 65 mi (105 km). The F layer (or Appleton layer) can be found above the E layer, above 93 mi (150 km), and it has the highest concentration of charged particles. Although its structure changes during the day, the F layer is a relatively constant layer, where extreme ultra-violet radiation is absorbed. It has two parts: the lower F1 layer, and the higher and more electron-dense F2 layer.

The free electrons in the ionosphere allow good propagation of electromagnetic waves, and excellent radio communication. The ionosphere is also the home for the aurora, a light display mostly in the night sky of the polar areas, caused by excited and light-emitting particles entering the upper atmosphere.

See also Atmospheric composition and structure; Aurora Borealis and Aurora Australialis

IRON

Iron is the fourth-most common element in Earth's **crust**, and the second-most common metal after **aluminum**. Its abundance is estimated to be about 5%. Sampling studies indicate that portions of Earth's core consist largely of iron, and the element is found commonly in the **Sun**, **asteroids**, and stars.

The chemical symbol for iron, Fe, comes from the Latin name for the element, *ferrum*. The most common ores of iron are hematite and limonite (both primarily ferric oxide; Fe_2O_3)

and siderite iron carbonate ($FeCO_3$). An increasingly important source of iron for commercial uses is taconite, a mixture of hematite and silica. Taconite contains about 25% iron. The largest iron resources in the world are found in China, Russia, Brazil, Canada, **Australia**, and India.

The traditional method for extracting pure iron from its ore is to heat the ore in a blast furnace with **limestone** and coke. The coke reacts with iron oxide to produce pure iron, while the limestone combines with impurities in the ore to form a slag that can then be removed from the furnace: $3C + 2Fe_2O_3 + \text{heat} \rightarrow 3CO_2 + 4Fe$.

Iron produced by this method is about 90% pure and is known as pig iron. Pig iron is generally too brittle to be used for most products and is further treated to convert it to wrought iron, cast iron, or steel. Wrought iron is an **alloy** of iron and any one of many different elements, while cast iron is an alloy of iron, **carbon**, and **silicon**. Steel is a generic term that applies to a very wide variety of alloys.

Iron is one of a handful of elements that have been known and used since the earliest periods of human history. In the period beginning about 1200 B.C. iron was so widely used for tools, ornaments, weapons, and other objects that historians and archaeologists have now named the period the Iron Age.

Iron is a silvery white or grayish metal that is ductile and malleable. It is one of only three naturally occurring magnetic elements, the other two being its neighbors in the **periodic table**: cobalt and nickel. Iron has a very high tensile strength and is very workable, capable of being bent, rolled, hammered, cut, shaped, formed, and otherwise worked into some desirable shape or thickness. Iron's **melting** point is 2,797°F (1,536°C) and its boiling point is about 5,400°F (3,000°C). Its density is 7.87 grams per cubic centimeter.

Iron is an active metal that combines readily with **oxygen** in moist air to form iron oxide (Fe_2O_3), commonly known as rust. Iron also reacts with very hot **water** and steam to produce hydrogen gas and with most acids and a number of other elements.

The number of commercial products made of iron and steel is very large indeed. The uses of these two materials can generally be classified into about eight large groups, including (1) automotive; (2) construction; (3) containers, packaging, and shipping; (4) machinery and industrial equipment; (5) rail transportation; (6) oil and gas industries; (7) electrical equipment; and (8) appliances and utensils.

A relatively small amount of iron is used to make compounds that have a large variety of applications, including dyeing of cloth, blueprinting, insecticides, water purification and sewage treatment, photography, additive for animal feed, fertilizer, manufacture of **glass** and ceramics, and wood preservative.

Iron is of critical important to plants, humans, and other animals. It occurs in hemoglobin, the molecule that carries oxygen in the blood. The U.S. Recommended Daily Allowance (USRDA) for iron is 18 mg (with some differences depending on age and sex) and it can be obtained from meats, eggs, raisins, and many other foods. Iron deficiency disorders, known as anemias, are not uncommon and can result in fatigue, reduced resistance to disease, an increase in respiratory and circulatory problems, and even death.

See also Chemical bonds and physical properties; Chemical elements; Earth, interior structure; Minerals

ISLAND ARCS

An island arc is a curving series of volcanic islands that are created through the collision of tectonic plates in an ocean setting. The particular type plate boundary that yields island arcs is called a **subduction zone**. In a subduction zone, one lithospheric (crustal) plate is forced downward under an upper plate. Continual tectonic movement pushes the lower plate deeper until it reaches a depth where temperatures are sufficient to begin to melt the subducted plate and form magmas. These magmas then rise through fractures and melt their way through the overlying **crust** to be extruded in the form of volcanoes. The volcanoes are generally andesitic in composition. If the overriding plate is oceanic, then volcanoes are extruded underwater and may eventually rise high enough to become islands. The volcanoes form in a line because the angle and rate of subduction, and hence the distance to the depth where **melting** occurs is consistent. Because the surface of Earth is curved, the line of volcanoes forms in an arcuate pattern in much the same manner as an arc is produced when a planar surface intersects a sphere.

Island arcs are usually accompanied by rapid **erosion** and **sedimentation** into accompanying basins. A back-arc basin occurs on the side of the overriding plate and a fore-arc basin forms toward the subducted plate side. Typically, a deep oceanic trench, such as the Marianas Trench, bounds an island arc on the oceanic side beyond the fore-arc basin.

The Aleutian Islands, the islands of Japan, and the Lesser Antilles are all examples of island arcs. The term volcanic arc is often interchanged with island arc, although volcanic arc can also refer to land-based volcanoes produced by subduction. The Andes Mountains are the result of a continental volcanic arc.

See also Andesite; Benioff zone; Subduction zone

ISOBARS

Isobars are lines that connect points of equal pressure on **weather** maps. The word originates from Greek, where *isos* means equal and *baros* means weight. Isobars are designed to describe the horizontal pressure distribution of an **area**, and are created from mean sea-level pressure reports. Because most of the weather stations are not located at sea level, but at a certain elevation, the pressure measured at every location has to be converted into sea level pressure before the isobars are drawn. This normalization is necessary because **atmospheric pressure** decreases with increasing altitude, and the pressure difference on the maps has to be due to the weather conditions, not due to the elevation differences of the locations.

Isobars are similar to height lines on a topographic map, and they are defined such that they can never cross each other.

An important consequence of air pressure differences is **wind**, because wind blows from areas of high pressure to areas of low pressure. The greater the pressure contrast and the shorter the distance, the faster the wind will blow, so closer isobars mean faster wind. Although the wind initially is controlled by the pressure differences, it is also modified by the influence of the **Coriolis effect** and friction close to Earth's surface. This is why isobars can only give a general idea about the wind direction and wind strength.

A rule observed first in 1857 by Dutch meteorologist Christoph Buys-Ballott (1817–1890) described the link between isobars and wind: in the Northern Hemisphere, if you stand with your back to the wind, the low pressure area is located on the left. In the Southern Hemisphere, standing with your back to the wind means that the low-pressure area is on the right. This is called Buys-Ballott's law.

Isobars can form certain patterns, making it useful for weather analysis or forecast. A cyclone or depression is an area of curved isobars surrounding a low-pressure region with winds blowing counterclockwise in its center in the Northern Hemisphere. An anticyclone is an area of curved isobars surrounding a high-pressure area, and the wind blows clockwise in the center of an anticyclone in the Northern Hemisphere. Open isobars forming a V-shape define a through of low pressure while high-pressured, N-shaped, open isobars define a ridge of high pressure. These features are usually predictable, and associated with a certain kind of weather, making it easier to forecast weather for a certain area.

See also Atmospheric pressure

ISOMORPH

Crystalline substances with chemical formulas that are similar, and with positively charged cations and negatively charged anions that are similar in size, may form **crystals** with the same structure. These isomorphous groups can be used in mineral classification.

One example is the halite group, which includes halite (NaCl), fluorite (CaF_2), and sylvite (KCl), among other **minerals**. The crystals that they form belong to the isometric crystal system, in which the unit cells (the smallest component of a crystal, which can repeat indefinitely in three dimensions) all have three axes of equal length oriented at angles of 90° to each other. Another example of an isomorphous group is the calcite group, which includes the carbonate minerals calcite ($CaCO_3$), magnesite ($MgCO_3$), rhodochrosite ($MnCO_3$), siderite ($FeCO_3$), and smithsonite ($ZnCO_3$). All of these minerals form crystals with the same symmetry, in this case in the hexagonal crystal system, where the unit cells of the crystals have three horizontal axes of equal length and one axis of different length, perpendicular to the other three. Sometimes, different minerals will have the same chemical composition (a situation called polymorphism). Aragonite has the same chemical composition as calcite, but crystallizes in the orthorhombic crystal system (where the unit cells have three axes of unequal length oriented at angles of 90° to each other). The aragonite group includes the minerals cerussite ($PbCO_3$), strontianite ($SrCO_3$), and witherite ($BaCO_3$). Similarity in cation and anion size is more important than chemical composition in isomorphism. Thus, uraninite (UO_2) and chlorargyrite (AgCl) both belong to the halite group, although their composition and properties are very different. In a solid solution, an isomorphous group of minerals exhibits of a range of mineral compositions between two end members. The **olivine** group forms such a **solid solution series** in the orthorhombic crystal system. The composition of olivine is usually given as $(Mg,Fe)_2SiO_4$, but it can range from pure forsterite (Mg_2SiO_4) to pure fayalite (Fe_2SiO_4). Isomorphism is also called isostructuralism.

See also Crystals and crystallography

ISOSTASY

Isostasy (also spelled Isotacy) is a geophysical phenomenon describing the force of **gravity** acting on crustal materials of various densities (mass per unit volume) that affects the relative floatation of crustal plates. Isostasy specifically describes the naturally occurring balance of mass in Earth's **crust**.

Continental crust and oceanic crust exist on **lithospheric plates** buoyant upon a molten, highly viscous aethenosphere. Within Earth's crustal layers, balancing processes take place to account for differing densities and mass in crustal plates. For example, under mountain ranges, the crust slumps or bows deeper into the upper mantle than where the land mass is thinner across continental plains. Somewhat akin to how **icebergs** float in seawater, with more of the mass of larger icebergs below the **water** than smaller ones, this bowing results in a balance of buoyant forces termed isostasy.

Isostasy is not a process or a force. It is simply a natural adjustment or balance maintained by blocks of crust of different mass or density.

Within Earth's interior, thermal energy comes from radioactive energy that causes convection currents in the core and mantle. Opposing convection currents pull the crust down into geosynclines (huge structural depressions). The sediments that have collected (by the processes of deposition that are part of the **hydrologic cycle**) are squeezed in the downfolds and fused into **magma**. The magma rises to the surface through volcanic activity or intrusions of masses of magma as batholiths (massive **rock** bodies). When the convection currents die out, the crust uplifts and these thickened deposits rise and become subject to **erosion** again. The crust is moved from one part of the surface to another through a set of very slow processes, including those in Earth's mantle (e.g., convection currents) and those on the surface (e.g. **plate tectonics** and erosion).

With isostasy, there is a line of equality at which the mass of land above sea level is supported below sea level. Therefore, within the crust, there is a depth where the total weight per unit **area** is the same all around the earth. This imaginary, mathematical line is called the "depth of compensation" and lies about 70 mi (112.7 km) below the earth's surface.

Isostasy describes vertical movement of land to maintain a balanced crust. It does not explain or include horizontal movements like the compression or folding of rock into mountain ranges.

Greenland is an example of isostasy in action. The Greenland land mass is mostly below sea level because of the weight of the **ice** cap that covers the island. If the ice cap melted, the water would run off and raise sea level. The land mass would also begin to rise, with its load removed, but it would rise more slowly than the sea level. Long after the ice melted, the land would eventually rise to a level where its surface is well above sea level; the isostatic balance would be reached again, but in a far different environment than the balance that exists with the ice cap weighing down the land.

Scientists and mathematicians began to speculate on the thickness of Earth's crust and distribution of landmasses in the mid-1800s. Sir George Biddell Airy (1801–1892) assumed that the density of the crust is the same throughout. Because the crust is not uniformly thick, however, the Airy hypothesis suggests that the thicker parts of the crust sink down into the mantle while the thinner parts float on it. The Airy hypothesis also describes Earth's crust as a rigid shell that floats on the mantle, which, although it is liquid, is more dense than the crust.

John Henry Pratt (1809–1871) proposed his own hypothesis stating that the mountain ranges (low density masses) extend higher above sea level than other masses of greater density. Pratt's hypothesis rests on his explanation that the low density of mountain ranges resulted from expansion of crust that was heated and kept its volume, but at a loss in density.

Clarence Edward Dutton (1841–1912), an American seismologist and geologist, also studied the tendency of Earth's crustal layers to seek equilibrium. He is credited with naming this phenomenon "isostasy."

A third hypothesis, eventually developed by Finnish scientist Weikko Aleksanteri Heiskanen (1895–1971) was a compromise between the Airy and Pratt models.

The model most accepted by modern geologists is the Hayford-Bowie concept. Advanced by American geodesists John Fillmore Hayford (1868–1925) and John William Bowie (1872–1940), geodesists, or specialists in geodesy, are mathematicians who study the size, shape, and measurement of Earth and of Earth forces (e.g., gravity). Hayford and Bowie were able to prove that the anomalies in gravity relate directly to topographic features. This essentially validated the idea of isostasy, and Hayford and Bowie further established the concept of the depth of isostatic compensation. Both gentlemen published books on isostasy and geodesy. Hayford was the first to estimate the depth of isostatic compensation and to establish that Earth has an oblate spherical shape (a bowed or ellipsoid sphere) rather than a true sphere.

See also Earth, interior structure

ISOTHERM

Isotherms are lines that connect points of equal **temperature** on **weather** maps, so at every point along a given isotherm the temperature values are the same. The word originates from Greek, where *isos* means equal and *therm* means heat. Isotherms are created from regularly scheduled, simultaneous temperature readings at different locations. For a proper comparison between the observation places, the measured temperature values are corrected for each location as if it was located at sea level. Isotherms help to visualize and interpret the horizontal temperature distribution of an **area** by showing patterns of temperature on a weather or **oceanography** map. Constructing a map of isotherms is an elementary step in temperature data analysis, and the process in general is called contouring. It can also be done for other parameters such as barometric pressure (**isobars**), geopotential height (isohypses), **dew point** temperature (isodrosotherms), **wind** speed (isotachs), and salinity (isohalines).

Isotherms are always smooth, labeled with the values, and mostly parallel to each other. Although the interval between the isotherms is arbitrarily chosen, within the same map it is a constant, and usually a round value. The value is selected such that the contour map both contains enough contours to show the patterns, and yet it is not crowded with too many lines. Because data is available only in the temperature observation points, interpolation should be used to create the isotherms between the measurement points. On the other hand, extrapolation to areas where no data is available is not acceptable. An isotherm should never split, cross, or touch another isotherm, because then at the crossing point it would have two different temperature values, which is physically impossible. Sometimes, contour maps are enhanced using color filling, when the area between pairs of isotherms is filled with special colors, so a particular color denotes the range of values between the two temperature values.

The relative spacing of the isotherms indicates the temperature gradient, the amount by which the temperature values vary across each unit of horizontal distance, in a direction perpendicular to the isotherms. The gradient is larger where the isotherms are closer. From the contour maps, areas of large gradient (regions where the temperature is changing quickly), as well as flat fields (regions where the temperature variation is not much) can be easily identified.

See also Isobars; Temperature and temperature scales

ISOTOPE • *see* ATOMIC MASS AND WEIGHT

J

JANSKY, KARL (1905-1950)

American radio engineer

One of the ways modern astronomers study the Universe is by tracing light waves through telescopes; another is by studying radio waves. The man who discovered the existence of these extraterrestrial radio waves, and thus founded radio **astronomy**, was Karl Jansky. Employed as an engineer in Bell Laboratories, New Jersey, Jansky was assigned the job of reducing static noise on transatlantic radio transmissions, and it was while inquiring into the origin of this static that he made his discovery.

The third of six children, Karl Guthe Jansky was born in Norman, Oklahoma, while that region was still a territory. His father, Cyril Jansky, was a college professor who taught electrical engineering and eventually became the head of the School of Applied Science at the University of Wisconsin. Jansky was named after Karl Guthe, a German-born physicist under whom his father had studied at the University of Michigan. Jansky attended the University of Wisconsin, where he played on the **ice** hockey team. He hoped to join the Reserve Officer's Training Program there but was diagnosed with a chronic kidney condition called Bright's disease; Jansky suffered from it all his life. He wrote his senior thesis on vacuum tubes and earned his B.S. in physics in June 1927. He stayed on at the University of Wisconsin for another year and supported himself by teaching while studying to complete the course work for his master's degree. He did not, however, write a thesis, and it would be years before he actually earned the degree.

After leaving the University of Wisconsin, Jansky applied for work at the Bell Communications Laboratories. The company was reluctant to hire him because of possible complications from Bright's disease. But Jansky's older brother, a professor of electrical engineering at the University of Minnesota, knew many Bell personnel. He intervened on behalf of his younger brother and secured the job for Jansky. Fearful of the stress he might suffer if he worked at their headquarters in New York City, the company assigned Jansky to work at its facilities in New Jersey.

Although transatlantic radio communication was possible in the early 1930s, it was very expensive and poor in quality. It cost 75 dollars to talk for three minutes from New York to London, and the transmissions, which occurred not through cables but through radio waves, were routinely interrupted by static. There were clicking, banging, crackling, and hissing noises that sometimes obliterated the conversation. At Bell, Harald Friis assigned Jansky the job of determining what was causing the static. This was in the summer of 1931, and the first step Jansky took to resolve the problem was to design a new antenna. He built a directional antenna that was capable of receiving a much wider range of wavelengths than conventional antennas of the time. He also developed a receiver that generated as little static as possible, to minimize its interference with his efforts to measure static from outside sources. Last, Jansky developed an averaging device for recording the variations in static. The antenna and the rest of the equipment were installed in Holmdel, New Jersey, a rural **area** where there would be very little interference from man-made radio signals.

The antenna that Jansky assembled at Holmdel was mounted on wheels and moved on a turntable. This allowed it to scan the sky in all directions once every 20 minutes; it could also be pointed at different heights above the horizon. Known as Jansky's "merry-go-round," the antenna is believed to have been the largest of its type at the time. It operated at 20 MHz or 14.6 meters. He categorized the static into three different types: local thunderstorms, distant thunderstorms, and steady static. Jansky was able to establish that thunderstorms were the source of clicks and bangs. But he observed of the last type of static, as quoted in *Mission Communications: The Story of Bell Laboratories*, that it was "a very steady hiss type static, the origin of which is not yet known."

Jansky recorded the intensity of the hiss-type static, and he observed that it peaked when the antenna was pointed at a certain part of the sky. At first, Jansky thought that the point of peak intensity followed the **Sun**, and he initially assumed that the static was solar-generated. However, as he continued to make his observations, he saw that the peaks were moving further and further from the Sun. Indeed, he observed that the peak intensities occurred every 23 hours and 56 minutes. This was perhaps the first time that Jansky truly considered the idea that this static could have an extraterrestrial origin.

Jansky knew little about astronomy, but after consulting some colleagues who did, he learned that while Earth takes 24 hours to rotate once on its axis in relation to the Sun, its **rotation** with respect to the stars is four minutes shorter. Known as a sidereal day, this phenomenon was precisely what Jansky had observed: peak intensities in static readings that occurred at intervals of 23 hours and 56 minutes. Although the existence of radio waves other than those generated by people on Earth had never even been considered as a possibility, Jansky did not doubt his findings. He had made a discovery that was entirely new, and he had done it by accident. He was also fortunate in another respect. His investigations were conducted at a time when the 11-year cycle of solar activity was at a minimum, which rendered the **ionosphere** transparent to 20 MHz wavelengths at night. If this had not been the case, solar flares would have drowned out the weak hisses from **space**, and Jansky would never have been able to measure them.

Jansky had observed that the static was most intense when his antenna was aimed at the center of the Milky Way, the galaxy in which Earth is located. His measurements indicated a direction of 18 hours right ascension and –10 degrees declination. Such a location put the peak static emissions in the constellation of Sagittarius. These observations led Jansky to form two hypotheses concerning the origin of the static; either radio sources are distributed much as the stars are in the galaxy, or the radio emissions come from stars like our own sun. Since Jansky never did pick up such emissions from the Sun (weaker types were found by others), he rejected the second theory; his investigations during a partial solar **eclipse** in 1932 also seemed to support his belief that the Sun was not emitting radio waves. The first hypothesis was supported by the fact that radio emissions were most intense from the center of the Milky Way, which contains the densest clusters of stars. Jansky also reasoned that the emissions from space would be found all along the **electromagnetic spectrum**, a hypothesis confirmed by later researchers.

It was in December 1932 that Jansky realized the extraterrestrial nature of the static he was studying, and he issued his first report on the subject that same month in a paper entitled "Directional Studies of Atmospherics at High Frequencies." He presented it to the Institute of Radio Engineers, but no one made much of his discovery. Indeed, Jansky's boss, Harald Friis, cautioned him against proposing that static came from extraterrestrial sources in case he should be proved wrong. In April 1933, Jansky presented a second paper on these radio signals at a meeting of the International Scientific Radio Union in Washington, D.C. On May 5, 1933, Bell Laboratories issued a press release on the subject, and the next day the *New York Times* headlined his work as "New Radio Waves Traced to the Center of the Milky Way." On May 15, NBC's Blue Network broadcast a sample of Jansky's "star noise" to the nation. It was described by reporters as "sounding like steam escaping from a radiator." Jansky presented his second paper again at the annual convention of the Institute of Radio Engineers (IRE) in June 1933, and it was published the following October.

While researching "star noise," Jansky worked on other projects. He designed a new receiver that could automatically change bandwidths, as well as studied the general effects of bandwidth on an incoming signal. When Bell realized that nothing could be done about the hiss-type static that Jansky was studying, they assigned him to a different project. Jansky wrote to his father in January 1934, as quoted in the *Invisible Universe Revealed*: "I'm not working on the interstellar waves anymore. Friis has seen fit to make me work on the problems of and methods of measuring noise in general. A fundamental and necessary work, but not near as interesting as interstellar waves, nor will it bring near as much publicity. I'm going to do a little theoretical research of my own at home on the interstellar waves, however." Although Jansky presented his findings to astronomers, they largely ignored the implications of his work. One reason was that they did not believe the Milky Way could possibly be such a giant and intensive radio source. Resources were also scarce during the Great Depression of the 1930s, and there was little money for equipment to pursue this discovery. But the primary reason Jansky's work was neglected was that astronomy was then an optical venture. No one had any idea what to do with radio measurements. Jansky was, however, able to use his papers on "star noise" as a thesis for his master's degree. The University of Wisconsin awarded him this degree on June 16, 1936.

Jansky made other contributions to the understanding of radio communications while he worked at Bell. He became adept at detecting the direction of arrival of short-wave transmissions from all over the globe, which led to a better understanding of the effects of radio propagation. The information Jansky gained helped refine the design of both transmitting and receiving antennas. He also conducted research on noise reduction in receivers and other circuits. The outbreak of World War II made it even more difficult for Jansky to pursue his research on "star noise." Still working for Bell Laboratories, he was assigned to a classified project concerning the development of direction finders for German U-boats or submarines. Jansky also worked on identifying particular transmitters by their "signatures," and his contributions led the military to issue him an Army-Navy citation. After the war, Jansky designed and developed frequency amplifiers which met the requirements of wide bandwidth and low noise.

Disappointed by the fact that he never had the time to investigate extraterrestrial radio waves further, Jansky applied for a teaching position at Iowa State University. He hoped that he would be able to use their facilities to further his research, but he was not hired. In 1948, the IRE made Jansky a fellow, but by this time Bright's disease was causing him to suffer from hypertension and heart problems. Although he tried to ward off the effects of his disease with specialized diets and health care, Jansky died at the age of 44 in 1950. He left behind his wife, Alice, to whom he had been married since August 3, 1929, and two children who were still teenagers.

Although never recognized for his contributions to radio astronomy during his lifetime, Jansky's work was honored 23 years later. In 1973, the General Assembly of the International Astronomer's Union adopted the Jansky as a unit of measurement. Defined as 10^{-26} watts per meter squared hertz, the Jansky measures intensity of radio waves.

JEMISON, MAE C. (1956-)

American astronaut

Mae C. Jemison had received two undergraduate degrees and a medical degree, had served two years as a Peace Corps medical officer in West **Africa**, and was selected to join the National Aeronautics and **Space** Administration's astronaut training program, all before her thirtieth birthday. Her eight-day space flight aboard the **space shuttle** *Endeavour* in 1992 established Jemison as the United States' first female African American space traveler.

Mae Carol Jemison was born in Decatur, Alabama, the youngest child of Charlie Jemison, a roofer and carpenter, and Dorothy (Green) Jemison, an elementary school teacher. Her sister, Ada Jemison Bullock, became a child psychiatrist, and her brother, Charles Jemison, is a real estate broker. The family moved to Chicago, Illinois, when Jemison was three to take advantage of better educational opportunities there, and it is that city that she calls her hometown. Throughout her early school years, her parents were supportive and encouraging of her talents and abilities, and Jemison spent considerable time in her school library reading about all aspects of science, especially **astronomy**. During her time at Morgan Park High School, she became convinced she wanted to pursue a career in biomedical engineering. When she graduated in 1973 as a consistent honor student, she entered Stanford University on a National Achievement Scholarship.

At Stanford, Jemison pursued a dual major and in 1977 received a B.S. in chemical engineering and a B.A. in African and Afro-American Studies. As she had been in high school, Jemison was very involved in extracurricular activities, including dance and theater productions, and served as head of the Black Student Union. Upon graduation, she entered Cornell University Medical College to work toward a medical degree. During her years there, she found time to expand her horizons by visiting and studying in Cuba and Kenya and working at a Cambodian refugee camp in Thailand. When she obtained her M.D. in 1981, she interned at Los Angeles County/University of Southern California Medical Center and later worked as a general practitioner. For the next two and a half years, she was the area Peace Corps medical officer for Sierra Leone and Liberia where she also taught and did medical research. Following her return to the United States in 1985, she made a career change and decided to follow a dream she had nurtured for a long time. In October of that year she applied for admission to NASA's astronaut training program. The *Challenger* disaster of January 1986 delayed the selection process, but when she reapplied a year later, Jemison was one of the 15 candidates chosen from a field of about 2000.

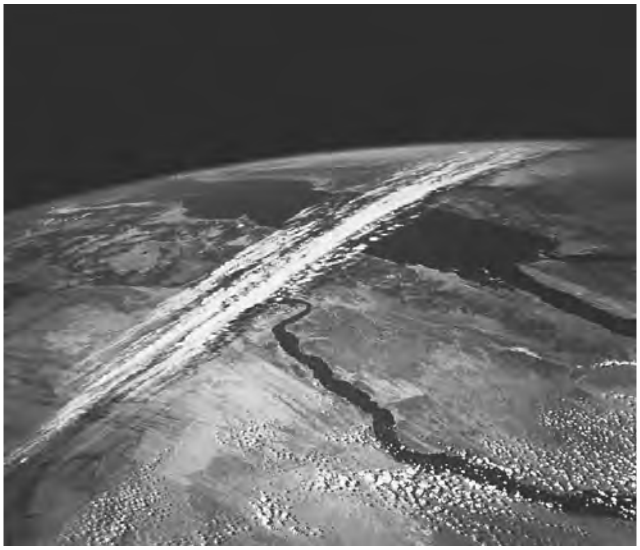
When Jemison was chosen in 1987, she became the first African-American woman ever admitted into the astronaut training program. After more than a year of training, she became an astronaut with the title of science-mission specialist, a job that would make her responsible for conducting crew-related scientific experiments on the space shuttle. On September 12, 1992, Jemison finally flew into space with six other astronauts aboard the *Endeavour* on mission STS–47. During her eight days in space, she conducted experiments on weightlessness and motion sickness on the crew and herself. Altogether, she spent slightly over 190 hours in space before returning to Earth on September 20. Following her historic flight, Jemison noted that society should recognize how much both women and members of other minority groups can contribute if given the opportunity.

In recognition of her accomplishments, Jemison received several honorary doctorates, the 1988 *Essence* Science and Technology Award, the *Ebony* Black Achievement Award in 1992, and a Montgomery Fellowship from Dartmouth College in 1993, and was named Gamma Sigma Gamma Woman of the Year in 1990. Also in 1992, an alternative public school in Detroit, Michigan—the Mae C. Jemison Academy—was named after her. Jemison is a member of the American Medical Association, the American Chemical Society, the American Association for the Advancement of Science, and served on the Board of Directors of the World Sickle Cell Foundation from 1990 to 1992. She is also an advisory committee member of the American Express Geography Competition and an honorary board member of the Center for the Prevention of Childhood Malnutrition. After leaving the astronaut corps in March 1993, she accepted a teaching fellowship at Dartmouth and also established the Jemison Group, a company that seeks to research, develop, and market advanced technologies.

See also History of exploration III (Modern era); Spacecraft, manned

JET STREAM

The jet stream is a narrow, fast, upper atmospheric **wind** current, flowing quasi-horizontally at high altitudes around Earth. By definition, the wind speed should be higher than 57 mph (92 kph) for jet streams, although the term is sometimes also erroneously used for all upper-level winds. The jet stream may extend for thousands of miles around the world, but it is only a few hundred miles wide and less than a mile thick. The wind speeds in the core sometimes can reach 200–300 mph (322–483 kph). These wind speeds within the jet stream that are faster than the surrounding regions are called jet streaks. On average, the jet stream flows from east to west, but it often meanders into northern or southern moving loops. Jet streams occur in both hemispheres, but the Southern Hemisphere jet streams show less daily variability. Jet streams can be



The jet stream over the Sahara Desert and the Nile River in northern Africa. ***NASA/Science Photo Library. Reproduced by permission.***

detected by drawing isothachs (the lines connecting points of equal wind speed) on a **weather** map.

Jet streams form in the upper **troposphere**, between 6.2–8.7 mi (10–14 km) high, at breaks in the tropopause, where the tropopause changes height dramatically. Jet streams are located at the boundaries of warm and cold air, above areas with strong **temperature** gradients. For example, the polar front, which separates cold polar air from warmer subtropical air, has a great temperature contrast along the frontal zone, leading to a steep pressure gradient. The resulting wind is the polar jet stream at about 6.2 mi (10 km) high, reaching maximum wind speed in winter. Sometimes the polar jet can split into two jets, or merge with the subtropical jet, which is located at about 8 mi (13 km) high, around 30 degrees **latitude**. A low-level jet stream also exists above the Central Plains of the United States, causing nighttime thunderstorm formation in the summertime. Over the subtropics, there is the tropical easterly jet, at the base of the tropopause in summertime, about 15 degrees latitude over continental regions. Near the top of the **stratosphere** exists the stratospheric polar jet during the polar winter.

Jet streams are well known since World War II. Detailed knowledge about the jet stream's location, altitude, and strength is essential not only for safe and efficient routing of aircrafts, but also for **weather forecasting**.

See also Atmospheric circulation; Coriolis effect; Troposphere and tropopause

JOHNSTON, HAROLD S. (1920-)

American geochemist

Harold S. Johnston has been recognized as one of the world's leading authorities in **atmospheric chemistry**. He was among the first to suggest that nitrogen oxides might damage Earth's ozone layer. Johnston's research interests have been in the field of gas-phase chemical kinetics and photochemistry, and his expertise has been employed by many state and federal scientific advisory committees on air pollution, motor vehicle emissions, and stratospheric pollution.

Harold Sledge Johnston was born on October 11, 1920, in Woodstock, Georgia, to Smith L. and Florine Dial Johnston. He graduated with a **chemistry** degree from Emory University in 1941 and, later that year, entered the California Institute of Technology as a graduate student. During the early 1940s, he was a civilian meteorologist attached to a United States Army unit in California and Florida, after which time he returned to graduate studies and earned his Ph.D. in chemistry and physics in 1948. That same year he married Mary Ella Stay, and the couple eventually had four children. Johnston was on the faculty of the chemistry department at Stanford University from 1947 to 1956 and the California Institute of Technology from 1956 to 1957. He then became a professor of chemistry at the University of California, Berkeley, serving as dean of the College of Chemistry from 1966 to 1970.

Johnston's introduction to **meteorology** occurred when he was a civilian scientist working on a defense project in World War II. In 1941, Roscoe Dickinson, Johnston's research director at the California Institute of Technology, was overseeing a National Defense Research Council project, with which Johnston became involved. Dickinson's group tested the effects of poisonous volatile chemicals on charcoals that were to be used in gas masks. Later, they studied how gas **clouds** moved and dispersed under different conditions in order to appraise coastal areas that might be vulnerable to chemical attacks.

In 1943, Johnston moved with the Chemical Warfare Service to Bushnell, Florida, where he worked with, and eventually headed, the Dugway Proving Ground Mobile Field Unit of the U.S. Chemical Warfare Service. This unit carried out test explosions to assess how the dispersion of gas was affected by meterological changes. While he was there, Johnston and John Otvos developed an instrument to measure the concentration of various gases in the air.

Johnston applied his meteorology work to his Ph.D. studies, which he resumed in 1945. He wrote his thesis on the reaction between **ozone**, a naturally occurring form of **oxygen**, and nitrogen dioxide, a pollutant formed during combustion. Later, during his tenure at Stanford, Johnston worked on a series of fast gas-phase chemical reactions. Using photo-electron multiplier tubes left over from the war, he pioneered a method of studying gas phase reactions that was a thousand times faster than existing techniques. Johnston then spent the years 1950 to 1956 researching high and low pressure limits of unimolecular reactions, and for the subsequent ten years, expanded his research to apply activated complex theory to elementary bimolecular reactions.

One of Johnston's most significant research efforts has been on the destruction of the ozone layer. This layer in the earth's upper atmosphere protects people from the Sun's **ultraviolet rays**. Chlorofluorocarbons (CFCs)—gaseous compounds often used in aerosol cans, refrigerants, and air conditioning systems—deplete this ozone layer, resulting in increased amounts of harmful radiation reaching the earth's surface. The Environmental Protection Agency has imposed production cutbacks on these harmful chemicals. Much like CFCs, nitrogen oxides also damage the ozone layer. During the late 1960s, the federal government financed the design and construction of two prototype supersonic transport (SST) aircraft. An intense political debate over whether the program should be expanded to construct five hundred SSTs was waged. Although Congress was split almost evenly, both houses voted to terminate the SST program in March, 1971. Johnston's articles and testimony suggesting the negative effects SSTs could produce on the atmosphere led two senators to introduce the **Stratosphere** Protection Act of 1971, which established a research program concerned with the stratosphere. The resulting 1971 program, with which Johnston was affiliated, was called the Climatic Impact Assessment Program (CIAP). Among other things, CIAP concluded that nitrogen oxides from stratospheric aircraft would further reduce ozone. CIAP recommended that aircraft engines be redesigned to reduced nitrogen oxide emissions.

Throughout his career, Johnston has served on many state and federal scientific advisory committees. In the 1960s, he was a panel member of the President's Science Advisory Board on Atmospheric Sciences and was on the National Academy of Sciences (NAS) Panel to the National Bureau of Standards. Johnston served on the California Statewide Air Pollution Research Center committee and the NAS Committee on Motor Vehicle Emissions during the early 1970s. He also served on the Federal Aviation Administration's High Altitude Pollution Program from 1978 to 1982 and the NAS Committee on Atmospheric Chemistry from 1989 to 1992. He has been an advisor to High Speed Civil Transport Studies for the National Aeronautics and **Space** Administration (NASA) since 1988.

Johnston is the author of the book *Gas Phase Reaction Rate Theory* and the author or coauthor of more than 160 technical articles. He is a member of the NAS, the American Academy of Arts and Sciences, the American Chemical Society, the American Physical Society, the American Geophysical Union, and the American Association for the Advancement of Science. Among Johnston's numerous awards are the 1983 Tyler Prize for Environmental Achievement, the 1993 NAS Award for Chemistry in Service to Society, and an honorary doctor of science degree from Emory University.

See also Global warming; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ozone layer depletion

JOINT AND JOINTING

Fractures in **rock** are classified according to the type of relative motion that has occurred across the fracture. Extensional fractures, also known as joints, are characterized by movement perpendicular to the fracture. The masses of rock separated by a joint moved away from each other, even if imperceptibly, when the joint was formed. Joints stand in contrast to faults, which are shear fractures across which the opposite sides slide past (rather than away from) each other. Rocks can undergo more than one episode of deformation during their existence, so it is possible for a fracture to begin as a joint and evolve into a fault as the stresses acting on the joint change through **geologic time**. The precise definition of a joint, however, is not universal and some geologists classify fractures as joints if there seems to have been only a small, but measurable, amount of shearing.

Joints formed in **coal** are known as cleats, and joints (or faults) filled with mineral deposits are known as veins. Volcanic rocks such as **basalt** contract as they cool, forming networks of columnar joints that divide the rock into regular polygonal columns such as those seen in Devil's Tower and Devil's Postpile National Monuments, USA.

Joints that are exposed at Earth's surface are often enlarged by chemical dissolution and **weathering**, particularly in soluble rocks such as **limestone** and, to a lesser degree, rocks such as calcite-cemented sandstones. Therefore, the width of joints in outcrops does not necessarily reflect the movement that created the joint.

Groups of joints sharing a similar three-dimensional geometry are known as joint sets. Like all fractures in rock, joints are irregular or wavy features rather than perfect planes. Therefore, joints in a set will have slightly different geometries and the separation of joints into sets can pose a difficult task for geologists. The combination of two or more sets of joints in a rock mass is a joint system.

Joints can also be described as being systematic or non-systematic. Systematic joints are those that are nearly planar (although never perfectly so) and occur in sets with regular spacing and orientation. Non-systematic joints are those with irregular or seemingly random geometry, spacing, and orientation. Although the terms are similar, systematic joints do not necessarily belong to joint systems and joint systems are not necessarily composed of systematic joints. It is possible, for example, for there to be a joint system composed of two sets of non-systematic joints.

The origin of joints and faults is studied by making detailed maps of rock fracture systems in the field and then applying mathematical techniques developed in the discipline of fracture mechanics. In fracture mechanics terminology, joints are known as Mode I fractures. Faults are Mode II or III fractures, depending on the direction of movement parallel to the fault surface. Studies have shown that rocks, like all other materials, contain innumerable microscopic flaws. When a rock is subjected to stress, either within Earth's **crust** or a laboratory-testing device, the fractures that most efficiently dissipate the stress grow in length and combine at the expense of other, less efficiently oriented, fractures. Fractures also perturb the distribution and intensity of stress in the adjacent rock, and the shape of a growing fracture can therefore be strongly influenced by the growth of its neighbors. Evidence for this phenomenon can be found in the field, where neighboring joints curve and then abruptly terminate against each other to form complicated, but understandable, patterns.

Because they are discontinuities in otherwise solid rock masses, joints can influence fluid flow through rocks and rock mass stability. Jointed rock has much higher **porosity and permeability** than intact rock of the same type, and can more easily transmit **petroleum**, **groundwater**, or ore-bearing geothermal fluids. Joints also form mechanical discontinuities that decrease the strength of rock, which is particularly important when rock is excavated during construction projects. Rockslides and rock falls also occur as a result of extensive joint sets or systems. Therefore, the identification and analysis of discontinuities such as joints, faults, and **bedding** planes is a critically important part of many applied geologic studies.

See also Faults and fractures; Field methods in geology

JUPITER • *see* SOLAR SYSTEM

JURASSIC PERIOD

In **geologic time**, the Jurassic Period—the middle of three geologic periods in the Mesozoic Era—spans the time from roughly 206–208 million years ago (mya) to approximately 146 mya.

The Jurassic Period contains three geologic epochs. The earliest epoch, the Lias Epoch, ranges from the start of the Jurassic Period to approximately 180 mya. The Lias Epoch is further subdivided into (from earliest to most recent) Hettangian, Sinemurian, Pliensbachian, and Toarcian stages. The middle epoch, the Dogger Epoch, ranges from 180 mya to 159 mya and is further subdivided into (from earliest to most recent) Aalenian, Bajocian, Bathonian, and Callovian stages. The latest epoch (most recent), the Maim Epoch, ranges from 159 mya to 144 mya and is further subdivided into (from earliest to most recent) Oxfordian, Kimmeridgian, and Tithonian stages.

During the Jurassic Period, the Pangaean supercontinent broke into continents recognizable as the modern continents. At the start of Jurassic Period, Pangaea spanned Earth's equatorial regions and separated the Panthalassic Ocean and the Tethys Ocean. Driven by **plate tectonics** during the Jurassic Period, the North American and European continents diverged, and the earliest form of the Atlantic Ocean flooded the spreading sea floor basin between the emerging continents. By mid-Jurassic Period, although still united along a broad region, what would become the South American and African Plates and continents became distinguishable in a form similar to the modern continents.

By the end of the Jurassic Period, **North America** and **South America** became separated by a confluence of the Pacific Ocean and Atlantic Ocean. Extensive flooding submerged much of what are now the eastern and middle portions of the United States.

By the end of the Jurassic Period, **water** separated South America from **Africa**, and the Australian and Antarctic continents were clearly articulated. The Antarctic continent began a slow southward migration toward the south polar region.

The Jurassic Period (in popular culture widely recognized as the "Age of the Dinosaurs") was named for the Jura Mountains on the Swiss-French border, an area where the classic formations were first identified and studied.

Large meteor impacts occurred at the start and end of the Jurassic Period (and later intensified during the subsequent **Cretaceous Period**). During the Jurassic Period itself, there is evidence of only one major impact—the Puchezh impact in Russia. The Manicouagan impact in **crust** now near Quebec, Canada, dates to the late **Triassic Period** just before the start of the Jurassic Period. A trio of impacts in areas now located in South Africa, the Barents Sea, and **Australia** occurred near the end of the Jurassic Period and start of the Cretaceous Period.

Although humans and dinosaurs never co-existed—in fact they are separated by approximately 63 million yeas of evolutionary time—the Jurassic Period's wealth of **fossils** have long stirred human imagination about life on Earth during that time. The abundant life of the Jurassic Period also left a legacy of organic remains that today provide an economically important source of fossil **fuels**. Many prominent oilfields date to the Jurassic Period (e.g., the North Sea fields).

See also Archean; Cambrian Period; Cenozoic Era; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Holocene Epoch; Marine transgression and marine recession; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Supercontinents; Tertiary Period

K

KARNS • *see* GLACIAL LANDFORMS

KARST TOPOGRAPHY

Karst is a German name for an unusual and distinct **limestone** terrain in Slovenia, called Kras. The karst region in Slovenia, located just north of the Adriatic Sea, is an **area** of barren, white, fretted **rock**. The main feature of a karst region is the absence of surface **water** flow. Rainfall and surface waters (streams, for example) disappear into a drainage system produced in karst areas. Another feature is the lack of topsoil or vegetation. In **geology**, the term karst **topography** is used to describe areas similar to that found in Kras. The most remarkable feature of karst regions is the formation of caves.

Karst landscapes develop where the **bedrock** is comprised of an extremely soluble calcium carbonate rock such as limestone, **gypsum**, or **dolomite**; limestone is the most soluble calcium carbonate rock. Consequently, most karst regions develop in areas where the bedrock is limestone. Karst regions occur mainly in the great sedimentary basins. The United States contains the most extensive karst region of the world. Other extensive karst regions can be found in southern France, southern China, Central America, Turkey, Ireland, and England.

Karst regions are formed when there is a chemical reaction between the **groundwater** and the bedrock. As rain, streams, and **rivers** flow over the earth's surface, the water mixes with the **carbon dioxide** that naturally exists in air. The water and **carbon** dioxide react to form a weak carbonic acid, which causes the **soil** to become acidic and corrode the calcium carbonate rock. The carbonate solution seeps into fissures, fractures, crevices, and other depressions in the rock. **Sinkholes** develop and the fissures and crevices widen and lengthen. As the openings get larger, the amount of water that can enter increases. The surface tension decreases, allowing the water to enter faster and more easily. Eventually, an underground drainage system develops. The bedrock is often hundreds of feet thick, extending from near the earth's surface to below the **water table**. Solution caves often develop in karst regions. Caves develop by an extensive enlargement and **erosion** of the underground drainage structure into a system of connecting passageways.

There are many variations of karst landscape, often described in terms of a particular landform. The predominant **landforms** are called fluviokarst, doline karst, cone and tower karst, and pavement karst. Some karst regions were etched during the **Ice** Age and may appear barren and very weathered (pavement karst). Other karst areas appear as dry valleys for part of the year and after seasonal **floods**, as a lake (one example of fluviokarst). In tropical areas, karst regions can be covered with **forests** or other thick vegetation. Sometimes, the underground drainage structure collapses, leaving odd formations such as natural bridges and sinkholes (doline karst). Tall, jagged limestone peaks are another variation (cone or tower karst).

See also Geochemistry; Hydrogeology; Weathering and weathering series

KELVIN SCALE • *see* TEMPERATURE AND TEMPERATURE SCALES

KEPLER, JOHANNES (1571-1630)

German astronomer

Johannes Kepler, the astronomer who determined the laws of planetary motion, was born in Weil in Würtemberg (now southwestern Germany) and seemed destined for a life in the church. He obtained a B.A. degree in theology in 1588 and entered the

Johannes Kepler.

University of Tübingen, one of the great centers of Protestant learning, in 1589. He graduated with an M.A. in 1591.

While at Tübingen, Kepler had learned mathematics, and when the high school in Graz, Austria, needed a mathematics teacher, he accepted the job. He turned out to be very poor at teaching; during his first year only a handful of students attended his lectures, and the following year he had no students at all. That gave him considerable free time to further his interest in **astronomy** and produce annual almanacs, which were often heavy on astrological content. He also raised additional income by casting horoscopes.

Kepler published a book in 1596 in which he devised a relationship involving the distances of the planets from the **Sun** with geometric solid objects such as cubes and spheres. His *Mysterium Cosmographicum* (Mystery of the universe) showed considerable knowledge of astronomy and brought him to the attention of **Tycho Brahe** and Galileo.

Beginning in 1597, life for Protestants in the Catholic-dominated **area** in which Kepler lived became unpleasant due to religious persecution, so Kepler moved to Prague (Czech Republic) in 1600, where he began working with Tycho Brahe.

Brahe was the antithesis of Kepler. Brahe had excellent eyesight that he used to compile the most detailed observational data in history; Kepler's eyesight was poor and he suffered from ill health all his life. Brahe was financially secure, and his extravagance drove Kepler, who always seemed to be in reduced circumstances, to distraction. Their working relationship was not optimal, but Brahe died within 18 months of Kepler's arrival.

Brahe had spent years making accurate observations of Mars with the naked eye and assigned Kepler the task of devising a theory of planetary motion using his observational data. Kepler, the mathematician, was superbly suited for this task, which would end up occupying the majority of his time for the next 20 years.

In 1604, before he had made much progress with Mars, a supernova blazed into view, and Kepler wrote two pamphlets about it. The supernova, like Brahe's Star in 1572, rivaled Venus in brightness and has since come to be known as Kepler's Star. He also wrote about applications of optics in astronomy and proposed a design for a **telescope**. After Galileo discovered the moons of Jupiter, Kepler used a telescope to prove to himself that they did, indeed, exist, and called them satellites.

The task with Mars proved extremely difficult. The circular orbit Kepler calculated did not agree exactly with Brahe's observations. Kepler's creative imagination came up with theory after theory to account for the discrepancy; at one point, after three years of work, he had a geometrical scheme that disagreed with one observation by only eight minutes of arc. (The full **Moon** is 31 minutes of arc in diameter; two objects four minutes of arc apart are barely noticeable to a person with average eyesight.) Kepler did not accept that Brahe's observations were anything less than perfect. He threw his scheme out and started again.

Kepler gave up on circles and epicycles and, out of desperation, tried working with an ellipse (oval). The results matched Brahe's data perfectly. Then he had to devise a law governing the variation of the speed of Mars as it moved along the ellipse. Here he got bogged down and lost his way, but he eventually formulated a simple law that matched observations. Finally, in 1609, Kepler published his first two laws of planetary motion: a planet orbits the Sun in an ellipse, not a circle as Nicholas Copernicus had believed; a planet moves faster when near the Sun, and slower when farther away. Kepler thought, incorrectly, that **magnetism** in the Sun was responsible for the variation.

The third law consumed Kepler's next ten years. In 1619, Kepler determined that the square of the time it takes a planet to orbit the Sun is equal to the cube of its average distance. In other words, once it is known how long it takes a planet to complete an orbit, its relative distance from the Sun can be calculated. However, it is still necessary to have a definite measured distance for one planet to act as a yardstick to determine the distance of the others.

It seems likely that Kepler happened on this formula, not by mathematical calculation, but by accident. He was constantly looking for mystical relations of numerical sequences to explain the "harmony of the heavens." In the same book in which the third law appears, Kepler devotes **space** to the "music of the spheres," assigning individual musical notes that each planet "sings."

Also in 1619, Kepler published a book on **comets** in which he supported Brahe's contention that comets were celestial objects and not manifestations of Earth's atmosphere. Kepler incorrectly believed them to be objects that moved in straight lines, but he had a remarkably accurate explanation of the Sun's part in producing a comet's tail.

Once again, religious persecution of Protestants caused Kepler to move, and he relocated to Ulm (Germany) in 1626. One year later he published his final great work: the *Rudolphine Tables,* a tabular collection of the motions of planets, dedicated to his former patron Emperor Rudolph II. They were used as the standard astronomical tables for the next century. Kepler died after a short illness at the age of 59.

See also Cosmology

KETTLES • *see* GLACIAL LANDFORMS

KIMBERLITIC DIAMOND • *see* DIAMOND

KINETIC AND POTENTIAL ENERGY • *see* ENERGY TRANSFORMATIONS

KRAKATOA • *see* VOLVANIC ERUPTIONS

K-SPAR • *see* FELDSPAR

K-T EVENT

The K-T event (Cretaceous-Tertiary event) refers to the mass extinction of the dinosaurs that took place approximately 65 million years ago (mya). In addition to the dinosaurs, most large land animals perished and an estimated 70% of all species on the planet became extinct.

In the early 1980s, a team of physicists and geologists documented a band of sedimentary **rock** in Italy that contained an unusually high level of the rare metal iridium (usually found on Earth's surface only as a result of meteor impacts). The scientists eventually argued that that the iridium layer was evidence of a large asteroid impact that spewed iridium contaminated dust into the atmosphere. Blown by global **wind** currents, the iridium eventually settled into the present thin sedimentary layer found at multiple sites around the world. Given the generalized dispersion of iridium the researchers argued that the impact was large and violent enough to cause dust and debris particles to reach high enough levels that they seriously occluded light from the **Sun** for a large expanse of Earth.

The subsequent reduction in photosynthesis was sufficient to drastically reduce land plant population levels and eventually drive many plant species to extinction. The reduction in plant population levels also provided evolutionary pressure on species nutritionally dependent upon plant life. Large life forms with high-energy demands (e.g., dinosaurs) were especially sensitive to the depleted dietary base. The adverse consequences of population reductions and extinctions of plant-eating life forms then rippled through the ecological web and food chain—ultimately resulting in mass extinction.

Calculations of the amount of iridium required to produce the observable layer (on average about a centimeter thick) yield estimates indicating that the asteroid measured at least 6 mi (10 km) in diameter. The **impact crater** from such an asteroid could be 100 mi (161 km) or more in diameter. Such an impact would result in widespread firestorms, earthquakes, and tidal waves. Post-impact damage to Earth's ecosystem occurred as dust, soot, and debris from the collision occluded the atmosphere to sunlight.

Based on **petroleum** exploration data, Canadian geologist Alan Hildebrand identified a major impact crater in the oceanic basin near what is now the Yucatan Peninsula of Mexico. The remains of the impact crater, termed the Chicxulub crater, measures more than 105 mi (170 km) in diameter. Argon dating places the Chicxulub impact at the expected Cretaceous-Tertiary **geologic time** boundary, approximately 65 mya.

Other geological markers are also indicative of a major asteroid impact approximately 65 mya (e.g. the existence of shock **quartz**, ash, and soot in sedimentary layers dated to the K-T event). Tidal wave evidence surrounding the **Gulf of Mexico** basin also dates to 65 mya.

Other scientists have argued that it was not a solitary impact that alone caused the mass extinction evidenced by the **fossil record**. At end of the prior **Cretaceous Period** and during the first half of the **Tertiary Period**, Earth suffered a series of intense and large impacts. Geologists have documented more that 20 impact craters greater than 6.2 mi (10 km) in diameter that date to the late Cretaceous Period. Large diameter impact craters were especially frequent during the last 25 million years of the Cretaceous Period (i.e., the Senonian Epoch).

The extinction of the dinosaurs and many other large species allowed the rise of mammals as the dominant land species during the **Cenozoic Era**.

See also Astronomy; Catastrophism; Dating methods; Evolution, evidence of; Fossil record; Fossils and fossilization; Historical geology; Meteoroids and meteorites; Paleocene Epoch

KYOTO TREATY • *see* ATMOSPHERIC POLLUTION

L

LAHAR

Lahars are debris flows associated with volcanoes, and can be further classified as either hot or cold depending on their **temperature**. The word lahar is of Indonesian origin, reflecting the frequency of volcanic debris flows in that region. Lahars can be mobilized by processes similar to those producing non-volcanic debris flows, most notably the transition of saturated **landslide** masses into **debris flow**, but can also be associated with the rapid **melting** of snow and **ice** by hot volcanic (pyroclastic) debris during an eruption. Earthquakes associated with volcanic activity can also trigger landslides that have the potential to mobilize into lahars.

Like non-volcanic debris flows, lahars move as fluid masses with the general consistency of wet concrete. Two characteristics of lahars that can make them particularly hazardous are their potentially very large volume and great velocity relative to many non-volcanic debris flows. For example, a lahar that occurred during an eruption of Cotopaxi **Volcano** (Ecuador) in 1877 traveled more than 186 mi (300 km) at an average velocity of 16.7 mph (27 kph). Lahars triggered by the 1980 eruption of Mount St. Helens traveled at an average velocity of 41.6 mph (67 kph). Eruptions of volcanoes mantled with snow or ice can also produce catastrophic lahars, as in the 1985 eruption of Nevado del Ruiz (Columbia) that killed some 23,000 people. Like non-volcanic debris flows, lahars are able to transport extremely large boulders or other objects because of the density of the flow, which is in most cases nearly the same as the intact debris from which the flow mobilized. Lahars are not necessarily large; some may involve as little as a few cubic centimeters of debris and pose little threat to life and limb.

Mapping and analyzing ancient lahar deposits are an important part of volcanic hazard assessment for volcanoes such as Mount Rainier and Mount Hood in the northwestern United States. Deposits left by past lahars provide insight into the likely size and frequency of future lahars. Trees and other organic material found ancient lahar deposits can be dated using radiometric methods, allowing geologists to assemble a chronology of lahar activity in the **area** around a volcano.

See also Catastrophic mass movements; Debris flow; Erosion; Landslide; Mass movement; Mass wasting; Mud flow

LAKE EFFECT SNOW • *see* BLIZZARDS AND LAKE EFFECT SNOWS

LAKES

Lakes and ponds are bodies of standing fresh **water** impounded in basins and depressions in the earth's continental **crust**. Lakes are temporary catchment basins for flowing surface and **groundwater**. **Freshwater** reservoirs form behind natural and man-made dams, surface water collects in topographic lows, and groundwater discharges into ephemeral lakes, but eventually all continental **runoff** drains to the ocean. Lakes provide humans with fresh drinking water, recreation areas and, in the case of the world's largest lakes, navigable waterways for ship traffic. Regional **climate** strongly affects the chemical and hydrological properties of lakes, and lake sediments often provide high-resolution records of climatic fluctuations. Lake basins typically fill with interlayered coarse and fine sediments, and organic material. Many ancient lacustrine deposits contain **petroleum** reservoirs. Because ponds, lakes, and inland **seas** are smaller and less well-mixed than the **oceans**, they are particularly susceptible to pollution.

Tectonic motion created the crustal basins and sags that contain the world's largest lakes. Elongate, deep lakes fill the axes of incipient divergent plate tectonic boundaries, or rift zones. The lakes of the East African Rift system—Lakes Turkana, Kiva, Tanganyika, and Malawi—fill the central grabens of the rift zone between the African and Somali **Lithospheric Plates**. Lake Baikal, the worlds deepest (5,370 ft,

Lake Powell, Arizona. © *Nik Wheeler/Corbis. Reproduced by permission.*

or 1,637 m) and most voluminous (Lake Baikal contains about 20% of the earth's fresh surface water) lake, occupies a rift valley in southern Siberia. Lakes also fill broad, shallow intercratonic basins that form during the earliest stages of continental **rifting**. Lake Eyre in central **Australia**, and Lakes Victoria and Chad in **Africa** are examples of lakes in shallow extensional basins.

Many modern lakes, including the **Great Lakes** of **North America**, occupy basins created by Northern Hemisphere **ice** sheets of the **Pleistocene Epoch**. The weight of the Laurentide and Eurasian ice sheets depressed large regions of the continental crust into the mantle, a phenomenon called glacial **isostasy**. Since the ice sheets retreated about 20,000 years ago, meltwater and stream runoff have collected in these broad depressions. Large regions of the northern continents—the Great Lakes region and the Scandinavian Peninsula for example—are presently undergoing rapid uplift, known as isotatic rebound, as these glacially depressed regions continue to readjust. Small ponds and lakes are also common in glacial environments. **Erosion** by moving ice carves **bedrock** depressions where lakes form, and leaves sills that impound glacial streams. Glacial sedimentary **landforms**, including **moraines**, kame terraces, and eskers serve as natural dams for glacial lakes. Glacial terrains are dotted with small ponds that fill circular depressions called kettles that form when ice blocks buried in glacial **till** deposits melt.

Lake basins also form in a number of other geologic environments. Small lakes and ponds are common in continental fold belts where outcrops of resistant bedrock divert and dam perennial streams. Abandoned meanders along low-gradient streams form circular lakes called oxbow lakes. Groundwater discharge zone lakes form where the top of the **saturated zone**, the **water table**, intersects the land surface. In humid and temperate climates, where the water table is close to the land surface, discharge lakes typically have an outlet stream. In arid regions, ephemeral groundwater discharges into closed, saline playa lakes that fill and dry seasonally.

Man-made lakes are a significant component of the earth's present-day **hydrologic cycle**. Most of the world's **rivers** have been dammed, creating reservoirs for human water supplies, recreation, and generation of electrical power. While reservoirs provide many benefits to human populations, they also force numerous readjustments to natural and artificial systems. Ecosystems must compensate for the loss of drowned habitats, human populations are displaced, and water quality is often compromised. Streams that have been segmented by dams regrade their equilibrium profiles, creating new patterns of erosion and deposition throughout the stream system. In fact, natural stream processes act to remove obstacles like dams by eroding the streambed below them, and depositing sediment in the reservoir above them. Poorly constructed and maintained dams are thus a safety hazard for downstream inhabitants.

Climatic factors control the chemical and hydrological properties of lakes. Regional variations of **temperature**, **precipitation**, and winds determine water levels, circulation patterns, vertical stratification, and the concentration of dissolved materials in lake water. The quantity and seasonality of rainfall in a drainage basin controls the balance between recharge and discharge that maintains lake level. Lake salinity is a function of the relative concentrations of dissolved ions and diluting water. During a **drought**, lake levels fall, salinity increases, and a lake can change from a permanent freshwater reservoir to an ephemeral saline lake. The Great Salt Lake in Utah is all that remains of Lake Bonneville, a much larger freshwater lake that existed during the wet period at the end of the Pleistocene Epoch. A 25% decrease in freshwater flow to the Aral Sea in central **Asia** has led to a 50% decrease in surface **area** and a four-fold increase in salinity since the 1960s.

Seasonal temperature variations, changes in the balance between precipitation and **evaporation**, and **wind** patterns affect lake circulation and stratification. High-latitude lakes that are subject to large diurnal temperature variations and strong winds are typically so well mixed that the water column is unstratified. Warm, stagnant low-latitude lakes are often permanently stratified. Without mixing, the lower water column of these stagnant, oligomictic lakes becomes depleted in **oxygen**, and aquatic plants choke the ecosystem in a process called eutrophication. Human water pollutants that contain phosphates—detergents for example—also encourage eutrophication. Temperate lakes that experience large seasonal temperature fluctuations undergo seasonal overturns in which a layer of cold surface water circulates to the bottom of the lake or the pond. This process of periodic restratification oxygenates the base of the water column and infuses lake-bottom ecosystems with nutrients. Lakebed sediments record these seasonal patterns, and can be used to deduce and date the regional climate history. Lake stratigraphers, or limnologists, use features like preserved pollens and winter-summer couplets of thin sedimentary laminae, called varves, to recreate the geochronology of a lake basin.

See also Hydrogeology

LAND AND SEA BREEZES

Land and sea breezes are **wind** and **weather** phenomena associated with coastal areas. A land breeze is a breeze blowing from land out toward a body of **water**. A sea breeze is a wind blowing from the water onto the land. Land breezes and sea breezes arise because of differential heating between land and water surfaces. Land and sea breezes can extend inland up to 100 mi (161 km) or manifest as local phenomena that quickly weaken with a few hundred yards of the shoreline. On average, the weather and cloud effects of land and sea breezes dissipate 20–30 mi (32–48 kph) inland from the coast.

Because water has a much higher heat capacity that do sands or other crustal materials, for a given amount of solar irradiation (**insolation**), water **temperature** will increase less than land temperature. Regardless of temperature scale, during daytime, land temperatures might change by tens of degrees, while water temperature change by less than half a degree. Conversely, water's high heat capacity prevents rapid changes in water temperature at night and thus, while land temperatures may plummet tens of degrees, the water temperature remains relatively stable. Moreover, the lower heat capacity of crustal materials often allows them to cool below the nearby water temperature.

Air above the respective land and water surfaces is warmed or cooled by conduction with those surfaces. During the day, the warmer land temperature results in a warmer (therefore less dense and lighter) air mass above the coast as compared with the adjacent air mass over the surface of water. As the warmer air rises by convection, cooler air is drawn from the ocean to fill the void. The warmer air mass returns to sea at higher levels to complete a convective cell. Accordingly, during the day, there is usually a cooling sea breeze blowing from the ocean to the shore. Depending on the temperature differences and amount of uplifted air, sea breezes may gust 15–20 mph (24–32 kph). The greater the temperature differences between land and sea, the stronger the land breezes and sea breezes.

After sunset, the air mass above the coastal land quickly loses heat while the air mass above the water generally remains much closer to it's daytime temperature. When the air mass above the land becomes cooler than the air mass over water, the wind direction and convective cell currents reverse and the land breeze blows from land out to sea.

Because land breezes and sea breezes are localized weather patterns, they are frequently subsumed into or overrun by large-scale weather systems. Regardless, winds will always follow the most dominant pressure gradient.

The updraft of warm, moist air from the ocean often gives rise to daytime cloud development over the shoreline. Glider pilots often take advantage of sea breezes to ride the thermal convective currents (sea breeze soaring). Although most prevalent on the sea coastline, land breezes and sea breezes are also often recorded near large bodies of water (e.g., the **Great Lakes**). In general, land breezes and sea breezes result in elevated **humidity** levels, high **precipitation**, and temperature moderation in coastal areas.

See also Adiabatic heating; Clouds and cloud types; Convection (updrafts and downdrafts); Seasonal winds; Weather forecasting methods

LANDFORMS

Landforms are the mesoscale topographic features that define a regional landscape. **Climate** and **plate tectonics** ultimately determine the system of processes—plate tectonic motion,

This mother and child are taking advantage of the sea breeze. *© Tim Kiusalaas/Corbis. Reproduced by permission.*

gravity, **erosion**, and deposition by **water**, **wind**, and ice—that interact in complex feedback loops to erect and destroy continental landforms. Climate, the regional pattern of seasonal **precipitation**, **temperature**, and wind-flow, varies with **latitude**, altitude, and physiographic location. Motion of Earth's **lithospheric plates**, called plate tectonics, determines the global geography of **mountain chains**, volcanoes, continental landmasses, and ocean basins, as well as the distribution of **rock** types. The morphology of landforms suggests the processes that created them, and landforms are clues to deciphering the present and past geological setting of a region.

Climate often dictates the mix of sedimentary processes acting to create landforms. For example, eolian, or wind-formed, landforms are common in arid environments, whereas **glacial landforms** like **moraines** and kettle ponds are found in cold regions with adequate snowfall. The abundance and seasonality of annual rainfall determines the intensity of **weathering** and erosion by flowing water. In rainy regions, a dendritic pattern of V-shaped **stream valleys** often dominates the landscape. Low-gradient stream valleys are filled with fluvial landforms like meandering channels, oxbow **lakes**, natural levees, and point bars, while sediment-choked mountain streams form broad, gravelly plains of intertwined channels and longitudinal bars.

Air currents also shape landscapes by sorting and reworking dry sediments in arid environments. Eolian landforms include numerous types of **sand dunes**: cresent-shaped barchans, merged barchans called transverse dunes, parabolic blowout pits, flow-parallel linear dunes, and large composite dunes called draas. Very large **dune fields** called ergs cover extensive **areas** of the major deserts. Seasonal temperature fluctuations affect the phase of water. Erosion by frozen surface water creates dramatic glacial features like **fjords**, hanging valleys, and cirques in high-latitude regions. **Evaporation** of standing water in hot, arid, **desert** environments forms a unique array of desert landforms, including ephemeral playa lakes and coarse-grained alluvial fans where mountain streams enter arid basins.

The tectonic plate setting and past **geology** of a region also affects its **topography**. Motion along tectonic plate boundaries creates tall mountain belts, volcanic chains, regions of broad uplift, and zones of subsidence. Escarpments, extensional valleys called grabens and pull-apart basins, and linear pressure ridges form along fault planes where rocks bodies move relative to one another. Gravity failure of tectonically over-steepened slopes creates **mass wasting** deposits like mudflows, slumps, and slides. Streams that follow outcrop patterns of folded sedimentary and metamorphic rocks create ridge and valley provinces. Resistant layers of horizontal strata in tectonically uplifted areas form broad tablelands. Caves, **sinkholes**, and other so-called karst features form when acidic rainwater falls on carbonate rock layers. Volcanic activity creates numerous distinctive landforms, including craters, **lava** flows, eroded volcanic necks, and, of course, the conical or shield-shaped volcanoes themselves. **Beach and shoreline dynamics** along continental margins form an array of coastal landforms, from erosional sea cliffs and stacks to depositional deltas, **barrier islands**, and spits.

The continents can be divided into physiographic landform provinces delineated by plate tectonic features and climatic zones. (**Antarctica** is an exception because **ice** covers about 90 percent of its land surface.) The Colorado Plateau, in the southwest United States, is an example of one such province, and a tour of its dramatic landscape illustrates the complex web of processes acting to sculpt its landforms. The Four Corners region is arid because the prevailing Pacific westerly winds have dropped most of their moisture in the high Sierras of California and Mexico before reaching it. Streams flowing onto the Plateau from the Rocky Mountains, however, provide ample erosional and depositional energy. The Plateau is a broad zone of tectonic uplift that has exposed a thick sequence of flat-lying sedimentary strata to deep incision of steep-walled canyons by flood-prone streams. Erosional remnants like flat-topped mesas, conical buttes, arches, and spires remain between the incised fluvial channels. Winds sort and transport grains of siliciclastic sand, creating dunes and sandblasting the landscape.

Humans have also affected **landscape evolution** in the modern southwest desert. Construction of dams along the major **rivers**, especially along the Colorado River, has led to stream regrading and a resulting change in the pattern of fluvial erosional and depositional landforms. Evaporation from man-made reservoirs, like Lake Powell and Lake Mead, has reduced the amount of water in downstream river segments and increased the **humidity** around the lakes. Water use by human cities, industries, and especially irrigated agricultural lands has changed the regional **hydrologic cycle**.

See also Canyon; Desert and desertification; Karst topography; Sedimentation; Stream valleys, channels and floodplains

LANDSCAPE EVOLUTION

A landscape is the cumulative product of interaction among dynamic geological processes over time. A region's **topography** and suite of characteristic **landforms** are, thus, clues to its geologic history. For example, the landscape of rugged, linear **mountain chains**, deep canyons, dry lake beds, and mesas in the United States' **desert** southwest tells a geologic story of fluvial and Eolian **erosion** acting during a period of increasing climatic aridity while plate tectonic forces caused crustal extension and uplift. Earth processes carve a landscape; dynamic interactions between processes control its **evolution** over time.

The earth's internal heat drives plate tectonic motion and influences the related processes of crustal uplift, magmatic intrusion, volcanism, crustal deformation, and seismic activity. External heat from the **Sun** forces circulation of Earth's atmosphere and hydrosphere, which in turn drives sedimentary processes such as weathering, erosion, transportation, and deposition. These forces, interacting under the influence of **gravity**, shape Earth's surface.

Earth processes interact in complex feedback systems. A change in the rate or directional alignment of one process—for example, an increase in rainfall or the abandonment of a river channel—may start a cascade of compensatory changes throughout a region. Plate-tectonic mountain-building and erosion interact in a negative feedback system that regulates the elevation of continental mountain belts. Elevation interacts with **temperature** and rainfall, the components of **climate**, to regulate rates of erosion. Climate interacts with vegetation to create soils. A balance between **precipitation** and temperature maintains a glacier. These are just a few examples of the dynamic processes that shape a regional landscape, and of the interactions that remold an existing array of landforms over time.

See also Eolian processes; Weathering and weathering series

LANDSLIDE

Landslide is a general term used to describe a variety of geologic processes involving the movement of fine-grained earth, coarse-grained debris, or **rock** down a slope under the influence of **gravity**. This broad definition of downslope movements includes falling, toppling, sliding, spreading, and flowing. Landslides can also occur under **water** (submarine landslides) and trigger tsunamis.

Commonly used landslide classification systems rely on separate terms to describe the type of movement (falling, toppling, sliding, spreading, or flowing) and the type of material involved. Unlithified material is classified as debris if it is predominantly coarse-grained (**sand**, gravel, cobbles, or boulders) and earth if it is primarily fine-grained (silt or **clay**). Thus, a **debris flow** would involve the down slope flow of predominantly coarse-grained material, whereas a debris slide would involve the sliding of the same kind of material along a well-defined slip surface. Additional detail can be included by specifying the rate of movement (which can range from several millimeters per year to tens of meters per second) and the water content of the moving mass (which can range from dry to very wet). Landslides moving at velocities faster than a few meters per minute, particularly when they are large, have the potential to cause catastrophic damage and loss of life. The volume of material involved in a landslide, however, is irrelevant to its classification and can range from a few cubic centimeters to several cubic kilometers. Landslides can also change modes as they move. For example, a debris slide may mobilize into a debris flow as the debris begins to move down slope.

The term mudslide, which is often used in news reports, does not exist within the classification systems used

Landslides are commonly considered to be fast-moving rocks rolling down a hillside. However, any sufficiently large section of land moving downhill, no matter how slowly, is considered to be a landslide. ***JLM Visuals. Reproduced by permission.***

by most geologists and engineers. It is an imprecise term that is best avoided.

Landslides occur when the forces tending to keep a **soil** or rock mass in place (resisting forces) are exceeded by those promoting movement (driving forces). Resisting forces most commonly arise due to the shear strength of the material acting over an **area**, such as the slip surface beneath a landslide, or as a consequence of engineered works such as retaining walls. The primary driving force—the component of the weight of the earth, debris, or rock mass acting parallel to the slope—and the force occurring when the potential landslide mass is accelerated during an **earthquake** can also trigger landsliding. Changing the geometry of a slope, for example by excavating some areas and placing fill in others during construction, can alter the balance of resisting and driving forces enough to trigger a landslide.

It is a widely held misconception that landslides occur because slopes are lubricated by water. Water does not act as a lubricant in landslides, but instead decreases the shear strength of the earth, debris, or rock by decreasing the normal force acting across a potential slip surface. It is well known from basic **physics** that the sliding of a block down an inclined plane is resisted by the product of the normal force acting on the plane and a coefficient of friction. Similarly, a decrease in the normal force acting across a potential slip surface will decrease the resistance to sliding. Sources of water leading to landsliding can include infiltrating rain and melted snow, leaking water pipes, and irrigation.

It is difficult to estimate the monetary costs of landslides because they can include both direct and indirect costs. Direct costs include damage to structures and roads, whereas indirect costs include items such as decreased property values, lost productivity, and the expense of driving longer distances when roads are blocked. Difficulties aside, in 1985 the National Research Council estimated that landslides cost between $1 billion and $2 billion per year in the United States alone. Estimates for other countries range from tens of millions to billions of dollars per year.

See also Catastrophic mass movements; Debris flow; Lahar; Mass movement; Mass wasting; Mud flow; Rockfall; Slump; Talus pile or talus slope

LATERAL MORAINE • *see* MORAINES

LATERITE

Laterite is a type of **soil** produced by intense, prolonged weathering, usually in tropical climates. Abundant **oxygen**, **water**, and warmth leach most water-soluble **minerals** from particles of parent **rock** and leave a nonsoluble residue enriched in hydroxides of **aluminum**, **iron**, magnesium, nickel, and titanium. Laterites high in specific **metals** are often strip-mined as ores.

Laterite rich in aluminum are termed aluminous laterite or bauxite. Aluminous laterite is formed from **clay** minerals such as kaolinite ($Al_4[Si_4O_{10}][OH]_8$) by the **leaching** of silica (SiO_2). The residue left by the leaching of silica, aluminum hydroxide ($Al[OH]_3$), is termed gibbsite. Gibbsite's dehydrated forms, diaspore and bohemite (both $HAlO_2$), are also common components of aluminous laterite. Aluminous laterite is the world's primary source of aluminum.

Laterite descended from **basalt** is rich in iron and nickel and is termed ferruginous laterite. Laterite formed from rocks particularly rich in nickel may contain a high percentage of the mineral garnierite ($[NiMg]_6Si_4O_{10}[OH]_8$). A continuum of mixed laterites exists between the aluminous and ferruginous extremes. Nickeliferous laterites are an important commercial source of nickel.

See also Soil and soil horizons; Weathering and weathering series

LATITUDE AND LONGITUDE

The concepts of latitude and longitude create a grid system for the unique expression of any location on Earth's surface.

Latitudes—also known as parallels—mark and measure distance north or south from the equator. Earth's equator (the great circle or middle circumference) is designated 0° latitude. The north and south geographic poles respectively measure 90° north (N) and 90° south (S) from the equator. The angle of latitude is determined as the angle between a transverse plane cutting through Earth's equator and the right angle (90°) of the **polar axis**. The distance between lines of latitude remains constant. One degree of latitude equals 60 nautical miles (approximately 69 statute miles, or 111 km).

Longitudes—also known as meridians—are great circles that run north and south, and converge at the north and south geographic poles. As the designation of 0° longitude is arbitrary, international convention, long held since the days of British sea superiority, establishes the 0° line of longitude—also known as the prime meridian—as the great circle that passes through the Royal National Observatory in Greenwich, England (United Kingdom). The linear distance between lines of longitude vary and is a function of latitude. The liner distance between lines of longitude is maximum at the equator and decreases to zero at the poles. There are 360 degrees of longitude, divided into 180° east and 180° west of the prime meridian. The line of longitude measuring 180° west is, of course, the same line of longitude measuring 180° east of the prime meridian and, except for some geopolitical local variations, serves as the international date line. Because Earth completes one **rotation** in slightly less than 24 hours, the angular velocity of rotation is approximately 15° of longitude per hour. This rate of rotation forms the basis for time zone differentiation.

The distance between lines of longitude varies in length at different latitudes, the distance lessening as latitude increases. At the equator, 69.171 statute miles separate lines of longitude, but by 30 degrees latitude, there are only 59.956 statute miles between lines of longitude. At 60 degrees latitude, only 34.697 statute miles separate longitudinal great circles at that latitude. At the poles, all lines of longitude converge.

Every point on Earth can be expressed with a unique set of latitude and longitude coordinates (i.e., lat/lon coordinates). Latitude—specified as degrees north (N) or south (S)—and longitude—specified as degrees east (E) or west (W)—are expressed in degrees, arcminutes, and arcseconds (e.g., a lat/lon of 39:46:05N, 104:52:22W specifies a point in Denver, Colorado).

Lines of latitude and longitude are usually displayed on maps. Although a variety of maps exist, because maps of Earth are two-dimensional representations of a curved three-dimensional oblate spherical surface, all maps distort lines of latitude and longitude. For example, with equatorial cylindrical projections (e.g., a Mercator **projection**), low-latitude regions carry little distortion. Higher latitudes suffer extreme distortion of distance because of erroneously converging lines of latitude (on the surface of the Earth they are parallel). Despite this disadvantage, Mercator projections remain useful in navigation because there is no distortion of direction and vertical lines drawn upon such a map indicate true north or south.

Many maps include inserts showing polar conic projections to minimize the distortion of latitude near the poles.

Although it is relatively easy to ascertain latitude—especially in the Northern Hemisphere where the altitude of the North Star (Polaris) above the horizon gives a fairly accurate estimate of latitude—the accurate determination of longitude proved to be one of great post-Enlightenment scientific challenges. The inability to accurately estimate longitude often proved fatal or costly in sea navigation. It was not until the eighteenth century, when British clockmaker **John Harrison** developed a chronometer that could accurately keep time onboard ship, that the problem of longitude was solved. An accurate clock allows navigators to compare, for example, the local time of observed high noon to the time at Royal National Observatory in Greenwich, England (Greenwich Mean Time or GMT). Knowing that Earth rotates at approximately 15° per hour, the time difference between local noon and GMT local noon is directly related to the degrees of longitude between the prime meridian and the observer's location.

Roald Amundsen, the first man to successfully reach the South Pole, is shown here using a sextant to determine his position. © *Hulton-Deutsch Collection/Corbis. Reproduced by permission.*

See also Analemma; Astrolabe; Astronomy; Cartography; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Earth (planet); Geographic and magnetic poles; Geography; GPS; Projection; Polar axis and tilt; Time zones

LAVA

Lava is molten **rock** that has been extruded onto Earth's surface. Before it reaches the surface, lava is called **magma**. Magma contains **crystals**, unmelted rock, and dissolved gasses, but it is primarily a liquid. **Oxygen**, silica, **aluminum**, **iron**, magnesium, calcium, sodium, potassium, titanium, and manganese are the primary elements found in magma, but other trace elements may be present in small amounts.

Viscosity of lava, or its resistance to flow, is determined by its **temperature** and chemical composition. In general, hotter lava that is low in silica flows much more readily than

Lava from Mt. Kilauea. This kind of lava has little silica in it, and is not explosive. When it dries, it will be referred to as pahoehoe lava. *JLM Visuals. Reproduced by permission.*

cooler, high-silica lava. The composition and viscosity of magma determines both its eruptive style and the rock type that will be formed when it cools. The three main types of lava, named for the rock types that they form, are basaltic (for **basalt**), rhyolitic (for **rhyolite**), and andesitic (for **andesite**).

Basaltic flows are the hottest, erupting at temperatures of 1,832–2,192°F (1,000–1,200°C). Basaltic lavas are high in calcium, magnesium, and iron, and low in silica, sodium, and potassium. Based on its composition, basalt is known as a **mafic** rock. The high temperature and low silica content allow basaltic lavas to flow readily and travel far. The Hawaiian Islands were built up from the seafloor from successive basaltic lava flows, forming large shield volcanoes. When basaltic lava erupts onto relatively flat land, flows known as flood basalts may spread out, with successive flows being piled on top of one another. The Columbia Plateau in Oregon and Washington and the Deccan Traps in northwestern India were formed from such eruptions. Viscosity differences within basaltic lavas result in two distinct flow types, characterized by their surface forms. Pahoehoe (pah-hoy-hoy), formed from less viscous lava, is named for the Hawaiian word for ropy. When solidified, the surface of a pahoehoe flow has a smooth texture that looks like coiled rope, which forms as the outer layer of the lava cools, then is dragged and folded as the flow continues to move beneath the surface. More viscous basalt flows give rise to aa (ah-ah) lava, characterized by blocky clumps. Aa flows move more slowly than do pahoehoe flows, allowing a thick surface layer to cool as the flow creeps forward. As the flow continues to move, the surface layer is broken into jagged pieces. Pahoehoe is common near the source of a basaltic flow, where the lava is hottest, and aa is normally found farther from the source, where the lava has cooled off significantly. Another unique feature of basaltic lava is the formation of pillow lavas. Mounds of ellipse shaped pillows form when basaltic lava is erupted under **water** or **ice**. As lava is extruded, the water (or ice) quickly chills the outer layer. Molten lava beneath the chilled surface eventually breaks through the skin and the process is repeated, resulting in a pile of lava pillows. Pillow lava deposits found on land indicate that the region was once under water.

Rhyolitic lavas are high in potassium, sodium, and silica, and low in calcium, magnesium, and iron. Rhyolite is a classified as a **felsic** rock. Its felsic composition, in addition to its low eruptive temperature (1,472–1,832°F, or 800–1,000°C), results in highly viscous lava that can just barely flow. Such lavas usually produce a volcanic dome that eventually is destroyed in a massive explosion as the viscous lava tries to escape. Lassen Peak in northeastern California, which last erupted between 1914 and 1917, is an example of a lava dome.

Andesitic lava has a composition that falls in between that of basaltic lava and that of rhyolitic lava. Andesite is hence classified as an intermediate rock. Andesitic lava flows more readily than rhyolitic lava, but not as easily as basaltic lava. Eruptions are characterized by a mixture of explosive activity and lava flows. Such eruptions form composite volcanoes, built up of alternating lava flows and pyroclastic deposits (deposits of debris ejected from the **volcano**). Composite volcanoes such as Mt. Fuji, in Japan, and Mt. Rainier, in Washington, are cone shaped.

See also Volcanic eruptions

LEACHING

Leaching usually refers to the movement of dissolved substances with **water** percolating through **soil**. Sometimes, leaching may also refer to the movement of soluble chemicals out of biological tissues, as when rainfall causes potassium and other ions to be lost by foliage.

Leaching occurs naturally in all soils, as long as the rate of water input through **precipitation** is greater than water losses by evapotranspiration. In such cases, water must leave the site by downward movement, ultimately being deposited to deep **groundwater**, or emerging through **springs** to flow into surface waters such as streams, **rivers**, and **lakes**. As the subterranean water moves in response to gradients of gravitational potential, it carries dissolved substances of many kinds.

Leaching is a highly influential soil-forming process. In places where the **climate** is relatively cool and wet, and the vegetation is dominated by conifers and heaths, the soil-forming process known as podsolization is important. In large part, podsolization occurs through the dissolving of **iron**, **aluminum**, calcium, organic matter, and other chemicals from surface soils and the downward leaching of these substances to lower soil depths, where they are deposited. Some solubilized materials may also be altogether lost from the soil, ending up in deep groundwater or in surface water. A different soil-forming process known as laterization occurs under the warm and humid climatic conditions of many tropical rain **forests**, where aluminum and iron remain in place in the surface soil while silicate is dissolved and leached downward.

The ability of water to solubilize particular substances is influenced to a substantial degree by the chemical nature of the solution. For example, highly acidic solutions have a relatively great ability to dissolve many compounds, especially those of **metals**. Aluminum (Al), for instance, is an abundant metallic constituent of soils, typically present in concentrations of 7–10%, but occurring as aluminum compounds that are highly insoluble, so they cannot leach with percolating water. However, under highly acidic conditions some of the aluminum is solubilized as positively charged ions (or cations). These soluble ions of aluminum are highly toxic to terrestrial plants and animals, and if they are leached to surface waters in large quantities they can also cause biological damage there. Aluminum ions are also solubilized from soils by highly alkaline solutions. A large salt concentration in soil, characterized by an abundance of dissolved ions, causes some ions to become more soluble through an osmotic extraction, also predisposing them more readily to leaching.

Soils can become acidified by various human activities, including emissions of air pollutants that cause acidic precipitation, certain types of agricultural fertilization, harvesting of biomass, and the mining of **coal** and sulfide **minerals**. Acidification by all of these activities causes toxicity of soil and surface waters through the solubilization of aluminum and other metals, while also degrading the fertility and acid-neutralization capacity of soil by causing the leaching of basic cations, especially calcium, magnesium, and potassium.

Another environmental problem associated with leaching concerns terrestrial ecosystems that are losing large quantities of dissolved nitrogen, as highly soluble nitrate. Soils have little capability to bind nitrate, so this anion leaches easily whenever it is present in soil water in a large concentration. This condition often occurs when disturbance, fertilization, or atmospheric depositions of nitrate and/or ammonium result in an availability of nitrate that is greater than the biological demand by plants and microorganisms, so this chemical can leach at relatively high rates. Terrestrial ecosystems of this character are said to be "nitrogen-saturated." Some negative environmental effects are potentially associated with severe nitrogen saturation, including an increased acidification and toxicity of soil and water through leaching of aluminum and basic cations (these positively charged ions move in companion with the negatively charged nitrate), nutrient loading to aquatic systems, potentially contributing to increased productivity there, and possibly predisposing trees to suffer decline and die back. If the nitrogen saturation is not excessive, however, the growth of trees and other vegetation may be improved by the relatively fertile conditions.

See also Caliche; Soil and soil horizons

LEAD

Lead (Pb) is a relatively common element in Earth crustal materials. Lead is a heavy, soft metal that is a solid at normal atmospheric and crustal pressures. Lead is reactive with **oxygen** and tarnishes and dulls when in contact with oxygen. Lead is not a good conductor of **electricity**, heat, sound, or other pressure vibrations.

Lead is found in Earth's **crust** at an abundance of about 13–20 parts per million. It rarely occurs as a free element, and is found most commonly as a compound in the form of galena (lead sulfide; PbS), anglesite (lead sulfate; $PbSO_4$), cerussite (lead carbonate; $PbCO_3$), and mimetite. Geochemically, lead is a moderately active metal that dissolves very slowly in **water.**

Lead is both ductile and malleable. These properties allow lead to be easily bent, cut, pulled, or otherwise worked to produce specific shapes. The **melting** point of lead is 621.3°F (327.4°C), its boiling point is about 3,180°F (1,749°C), and its density is 11.34 grams per cubic centimeter.

The largest producers of lead in the world are **Australia**, China, the United States, Peru, Canada, Mexico, and Sweden. In the United States, more than 90% of all the lead produced comes from a single state, Missouri. Lead is extracted from its ores by first converting the ore to lead oxide and then heating the oxide with charcoal (pure **carbon**). The lead produced by this process is usually not very pure and can be further refined electrolytically.

Over the past decades, evidence has mounted indicating lead as a significant environmental hazard. Low levels of lead in products (e.g., paint) can accumulate in tissues over time. As a result, many manufactured items (e.g., batteries) now have or seek lead substitutes or provide for contained disposal.

See also Chemical elements; Minerals

LEHMANN, INGE (1888-1993)

Danish geophysicist

Trained as a mathematician and an actuary, Danish geophysicist Inge Lehmann used painstaking analyses, measurements and observations of shock waves generated by earthquakes to propose in 1936 that the earth had a solid inner core. Throughout her long career, which extended far beyond her official retirement in 1953, Lehmann conducted research in **Europe** and **North America** and was active in international scientific organizations including serving as the first president and a founder of the European Seismological Federation.

Lehmann was one of two daughters born to Alfred Georg Ludvig Lehmann, a University of Copenhagen professor of psychology, and Ida Sophie Torsleff. As a child, she attended and graduated from the first coeducational school in

Denmark, an institution founded and run by Hanna Adler, the aunt of future Nobel Prize winning physicist **Niels Bohr**. She began her university education by studying mathematics at the University of Copenhagen from 1907 to 1910. She continued her mathematical studies the following year at Cambridge University in England before returning to Denmark, where she worked as an actuary from 1912 to 1918. She also continued her formal education. In 1920, Lehmann earned her masters degree in mathematics from the University of Copenhagen and later studied mathematics at the University of Hamburg. In 1925, Lehmann began her career in **seismology** as a member of the Royal Danish Geodetic Institute and helped install the first seismographs at her Copenhagen office. "I was thrilled by the idea that these instruments could help us to explore the interior of the earth, and I began to read about it," she was quoted in a 1982 article published in the *Journal of Geological Education*. Lehmann later helped establish **seismograph** stations in Denmark and Greenland.

After further study with seismologists in France, Germany, Belgium, and the Netherlands, and after earning a M.S. degree in geodesy from the University of Copenhagen in 1928, Lehmann was named chief of the Royal Danish Geodetic Institute. In that position, held until her retirement in 1953, Lehmann was Denmark's only seismologist for more than two decades. She was responsible for supervising the Denmark's seismology program, overseeing the operation of the seismograph stations in Denmark and Greenland, and preparing the institute's bulletins.

Despite this heavy workload, Lehmann still found time to explore scientific research. In 1936, she published her most significant finding, the discovery of the earth's inner core, under the simple title of "P." The letter P stood for three types of waves generated by Pacific earthquakes that Lehmann had been carefully observing through the planet for ten years. By studying the shock waves generated by earthquakes, recorded on seismographs as travel-time curves, she theorized that the earth has a smaller solid inner core. Within a few years, work by other scientists, including Harold Jeffreys and Beno Gutenberg, substantiated her findings.

Lehmann continued her research well after her retirement in 1953, exploring the nature of the planet's interior in Denmark, in Canada at the Dominion Observatory in Ottawa and in the United States at the University of California at Berkeley, the California Institute of Technology, and the Lamont Doherty Earth Observatory at Columbia University. She was a named a fellow of both the Royal Society of London and Edinburgh and was named to the Royal Danish Academy of Science and Letters and the Deutsche Geophysikalische Gesellschaft. In 1971, she was awarded the William Bowie Medal of the American Geophysical Union in recognition of her "outstanding contributions to fundamental geophysics and unselfish cooperation in research." She was also awarded honorary doctorates by the University of Copenhagen and Columbia University.

Lehmann remained single throughout her long and productive life. Her interests were not restricted to science. She was concerned with the poor in her native Denmark and the plight of European refugees. Travel in conjunction with her work also afforded her frequent opportunities to pursue two of her hobbies—visiting art galleries throughout Europe and the United States, and the outdoors. Lehmann enjoyed hiking, mountain climbing, and skiing. She died at the age of 105.

LIBBY, WILLARD F. (1908-1980)

American chemist

Chemist Willard F. Libby developed the radiocarbon dating technique used to determine the age of organic materials. With applications in numerous branches of science, including archaeology, **geology**, and geophysics, radiocarbon dating has been used to ascertain the ages of both ancient artifacts and geological events, such as the end of the **Ice** Age. In 1960, Libby received the Nobel Prize for his radiocarbon dating work. During World War II, Libby worked on the Manhattan Project to develop an atomic bomb and was a member of the Atomic Energy Commission for several years in the 1950s. An outspoken scientist during the Cold War between the United States and the former Soviet Union, Libby advocated that every home have a fallout shelter in case of nuclear war. Libby, however, was a strong proponent of the progress of science, which he believed resulted in more benefits than detriments for the human race.

Willard Frank Libby was born to Ora Edward and Eva May Libby on a farm in Grand Valley, Colorado. In 1913, the family, which included Libby and his two brothers and two sisters, moved to an apple ranch north of San Francisco, California, near Sebastopol, where Libby received his grammar school education. A large boy who would eventually grow to be 6 feet 3 inches tall, Libby developed his legendary stamina while working on the farm. He played tackle for his high school football team and was called "Wild Bill," a nickname used by some throughout Libby's life. After graduating from high school in 1926, Libby enrolled at the University of California, Berkeley. He made money for college by building apple boxes, earning one cent for each box and sometimes $100 in a week. "I was the fastest box maker in Sonoma County," he told Theodore Berland, who interviewed Libby for his book *The Scientific Life*.

Although Libby was interested in English literature and history, he felt obligated to seek a more lucrative career and entered college to become a mining engineer. By his junior year, however, Libby became interested in **chemistry**, spurred on by the discussions of his boarding house roommates, who were graduate students in chemistry. Libby took on a heavy course load, focusing on mathematics, **physics**, and chemistry. After receiving his B.S. in chemistry in 1931, he entered graduate school at Berkeley and studied under the American physical chemist Gilbert Newton Lewis and Wendell Latimer, who were pioneering the physical chemistry field.

Libby received his Ph.D. in 1933 and was appointed an instructor in chemistry at Berkeley. After the Japanese bombed Pearl Harbor in 1941, Libby, who was on a year sabbatical as a Guggenheim Fellow at Princeton University, joined a group of scientists in Chicago, Illinois, to work on the Manhattan

Project, a government-sponsored effort to develop an atomic bomb. During this time, he worked with American chemist and physicist **Harold Urey** at Columbia University on gaseous diffusion techniques for the separation of uranium isotopes (isotopes are different forms of the same element having the same **atomic number** but different atomic weights). After the war, he accepted an appointment as a professor of chemistry at the University of Chicago and began to conduct research at the Institute of Nuclear Studies.

In 1939, scientists at New York University had sent radiation counters attached to balloons into the earth's upper atmosphere and discovered that neutron showers were created by cosmic rays hitting atoms. Further evidence indicated that these neutrons were absorbed by nitrogen, which then decayed into radioactive carbon–14. In addition, two of Libby's former students, Samuel Ruben and Martin Kamen, made radioactive carbon–14 in the laboratory for the first time. They used a cyclotron (a circular device that accelerates charged particles by means of an alternating electric field in a constant **magnetic field**) to bombard normal carbon–12 with neutrons, causing it to decay into carbon–14.

Intrigued by these discoveries, Libby hypothesized that radioactive carbon–14 in the atmosphere was oxidized to **carbon dioxide**. He further theorized that, since plants absorb **carbon** dioxide through photosynthesis, all plants should contain minute, measurable amounts of carbon–14. Finally, since all living organisms digest plant life (either directly or indirectly), all animals should also contain measurable amounts of carbon–14. In effect, all plants, animals, or carbon-containing products of life should be slightly radioactive.

Working with Aristide von Grosse, who had built a complicated device that separated different carbons by weight, and graduate student Ernest C. Anderson, Libby was successful in isolating radiocarbon in nature, specifically in methane produced by the decomposition of organic matter. Working on the assumption that carbon–14 was created at a constant rate and remained in a molecule until an organism's death, Libby thought that he should be able to determine how much time had elapsed since the organism's death by measuring the **half-life** of the remaining radiocarbon isotopes. (Half-life is a measurement of how long it takes a substance to lose half its radioactivity.) In the case of radiocarbon, Libby's former student Kamen had determined that carbon–14's half-life was 5,370 years. So, in approximately 5,000 years, half of the radiocarbon is gone; in another 5,000 years, half of the remaining radiocarbon decays, and so on. Using this mathematical calculation, Libby proposed that he could determine the age of organisms that had died as many as 30,000 years ago.

Because a diffusion column such as von Grosse's was extremely expensive to operate, Libby and Anderson decided to use a relatively inexpensive Geiger counter to build a device that was extremely sensitive to the radiation of a chosen sample. First, they eliminated 99% of the background radiation that occurs naturally in the environment with 8-inch-thick (20 cm) **iron** walls to shield the counter. They then used a unique chemical process to burn the sample they were studying into pure carbon lampblack, which was then placed on the inner walls of a Geiger counter's sensing tube.

Libby first tested his device on tree samples, since their ages could be determined by counting their rings. Next, Libby gathered tree and plant specimens from around the world and discovered no significant differences in normal age-related radiocarbon distribution. When Libby first attempted to date historical artifacts, however, he found his device was several hundred years off. He soon realized that he needed to use at least several ounces of a material for accurate dating. From the Chicago Museum of Natural History, Libby and Anderson obtained a sample of a wooden funerary boat recovered from the tomb of the Egyptian King Sesostris III. The boat's age was 3,750 years; Libby's counter estimated it to be 3,261 years, only a 3.5 % difference. Libby spent the next several years refining his technique and testing it on historically significant, and sometimes unusual objects, such as prehistoric sloth dung from Chile, the parchment wrappings of the Dead Sea Scrolls, and charcoal from a campsite fire at Stonehenge, England. Libby saw his new dating technique as a way of combining the physical and historical sciences. For example, using wood samples from **forests** once buried by **glaciers**, Libby determined that the Ice Age had ended 10,000 to 11,000 years ago, 15,000 years later than geologists had previously believed. Moving on to man-made artifacts from **North America** and **Europe** (such as a primitive sandal from Oregon and charcoal specimens from various campsites), Libby dispelled the notion of an Old and New World, proving that the oldest dated human settlements around the world began in approximately the same era. For many years after Libby's discovery of radiocarbon dating, the journal *Science* published the results of dating studies by Libby and other scientists from around the world. In 1960, Libby was awarded the Nobel Prize in chemistry for his work in developing radiocarbon dating. In his acceptance speech, as quoted in *Nobel Prize Winners,* Libby noted that radiocarbon dating "may indeed help roll back the pages of history and reveal to mankind something more about his ancestors, and in this way, perhaps about his future." Further progress in radiocarbon dating techniques extended its range to approximately 70,000 years.

In related work, Libby had shown in 1946 that cosmic rays produced tritium, or hydrogen–3, which is also weakly radioactive and has a half-life of 12 years. This radioactive form of hydrogen combines with **oxygen** to produce radioactive **water**. As a result, when the United States tested the Castle hydrogen bomb in 1954, Libby used the doubled amount of tritium in the atmosphere to date various sources of water, deduce the water-circulation patterns in the United States, and determine the mixing of oceanic waters. He also used the method to date the ages of wine, since grapes absorb rain water.

In 1954, U.S. President Dwight D. Eisenhower appointed Libby to the Atomic Energy Commission (AEC). Although he continued to teach graduate students at Chicago, Libby drastically reduced his research efforts and plunged vigorously into his new duties. Previously a member of the commission's General Advisory Committee, which developed commission policy, Libby was already acquainted with the inner workings of the commission. He soon found himself embroiled in the nuclear fallout problem. Upon a recommendation by the Rand Corporation in 1953, Libby formed and directed Project Sunshine and became the first person to measure nuclear fallout in everything from dust, **soil**, and rain to human bone.

As a member of the AEC, Libby testified before the U.S. Congress and wrote articles about nuclear fallout. He noted that all humans are exposed to a certain amount of natural radiation in sources such as drinking water. He went on to point out that the combination of the body's natural **radioactivity**, cosmic radiation, and the natural radioactivity of the earth's surface was more hazardous than fallout resulting from nuclear testing. Libby assumed, and most scientists of the day concurred, that the effects of nuclear fallout from careful testing on human genetics were minimal.

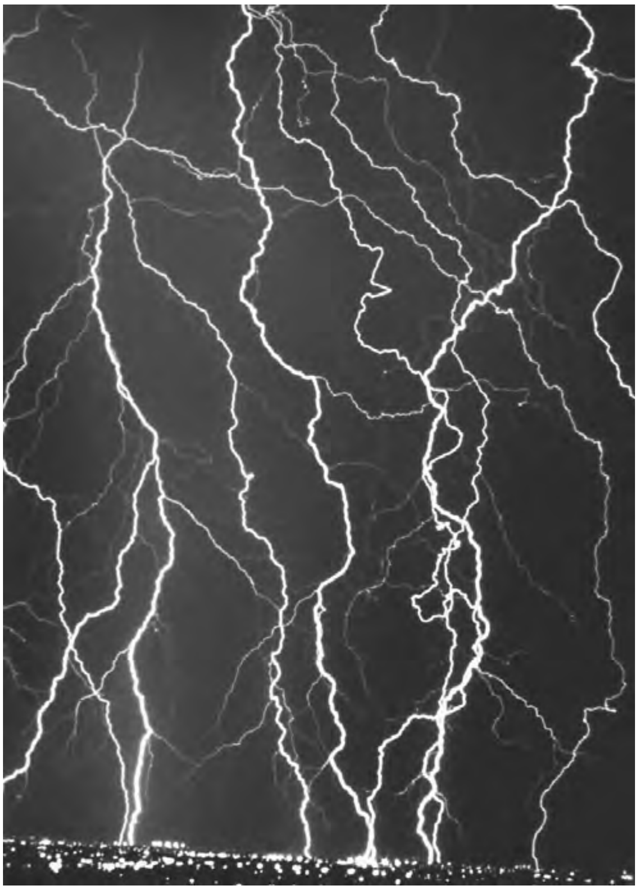
See also Chemical bonds and physical properties; Chemical elements; Cosmic microwave background radiation; Dating methods; Nuclear winter

LIFT AND LIFTING BODIES • *see* AERODYNAMICS

LIGHTNING

Lightning is a large electrical discharge produced by well-developed thunderstorms, a huge spark followed by a rumbling noise of **thunder**. Lightning can happen within the cloud (intra-cloud), between two **clouds** (inter-cloud), or from the cloud to the ground. A lightning bolt can heat the air as much as five times hotter than the surface **temperature** of the **Sun**, or about 54,000°F (30,000°C). This heated air causes expansion in the air as an explosion, starting a shock wave that turns into a sound wave upon reaching the human ear. Thunder travels in all directions (radially) from the lightning at the speed of sound, approximately 738 mph (1,188 kph) at sea level. Because it takes the sound about five seconds to travel each mile (about three seconds for one kilometer), the time between the lightning and the thunder can give a rough estimate of how far an observer is from a thunderstorm.

The quick flash that can be seen as lightning occurs as a complex series of events. In order to have lightning, separate regions of electrical charges must be present in a cumulonimbus cloud. There are several hypotheses as to how this occurs. One mechanism may involve falling **ice** particles within the cloud that transfer ions. This results in a positively charged upper part and a negatively charged middle part in the cloud. The bottom of the cloud is also mostly negatively charged, causing part of the ground underneath to become positively charged. In the insulating dry air an electrical field builds up, and when it reaches a threshold potential, the air is no longer insulating and, as a current flows, lightning occurs.



Lightning strikes over Tuscon, Arizona. ***Keith Kent/Peter Arnold, Inc. Reproduced by permission.***

Cloud-to-ground lightning (arguably the best understood among the different types of lightning) starts inside the cloud when a critical value of the localized electric field is reached along a path, so a surge of electrons will move to the cloud base, then gradually down to the ground. A short (165 ft, or 50 m) and narrow (4 in, or 10 cm) conducting channel is created by ionized air molecules, which are produced by the electron flow out of the cloud. These surges of electrons move downward in a series of steps for about 165–328 ft (50–100 m), then they stop for about 50-millionths of a second, and continue for another 165 ft, creating a stepped leader form of transit. Near the ground, a current of positive charge goes up from the ground to meet the stepped leader, and when they meet, many electrons flow into the ground, and a bright return stroke moves up, following the path of the stepped leader up to the cloud, releasing heat, thunder, and charges. The subsequent leader is called the dart leader and, for subsequent flashes, the same processes reoccur in a similar cycle. Usually, a lightning flash has approximately three or four leaders, each of them accompanied by a return stroke.

To distinguish the several different appearances of lightning, the forms are assigned special names. Heat lightning (also termed clear-air lightning) occurs when lightning can be seen but the following thunder cannot be heard. Forked lightning occurs when a dart leader moving toward the ground diverges from the original path of the stepped leader, so that the lightning seems to be crooked or forked. When the **wind** moves the ionized channel between the return strokes, the lightning looks like a ribbon hanging from a cloud, so it is called a ribbon lightning. Bead lightning looks like a series of beads on a string, and it occurs as the lightning channel disintegrates. Sheet lightning appears as a white sheet, and it occurs either when clouds obscure the lightning, or when the lightning flash happens within a cloud. St. Elmo's Fire, named after the patron of sailors, is a corona discharge, a nonstop supply of sparks in the air, which happens when a positive current moves up on pointed objects. Ball lightning often appears as a luminous, floating sphere in the air. The various mechanisms underlying the varying forms of lightning remain a subject of intensive meteorological research.

During a thunderstorm, usually the tallest object in the **area** is struck because this provides the most rapid form of current transit to lowest energy state. At any moment, there are about 2,000 thunderstorms worldwide, generating about 100 lightning flashes per second. A lightning stroke can deliver a current as great as 100,000 amperes, which can cause electrocution in humans and animals. About 100 people die in a year in the United States alone from lightning, and lightning causes billions of dollars in damage each year.

See also Atmospheric circulation; Atmospheric composition and structure; Atoms; Clouds and cloud types; Meteorology

LIMESTONE

Limestone is a sedimentary **rock** composed almost entirely of the mineral calcite (calcium carbonate, $CaCO_3$). The precursor calcium-carbonate sediment that existed prior to **lithification** of limestone can be of several types. These sediment types include carbonate mud, carbonate fossil fragments, carbonate pellets and rip-up clasts, and ooids. Carbonate mud is made of microcrystalline calcite **crystals** (crystals of a few microns in size) that form directly from seawater and from the disintegration of some calcareous marine algae. Carbonate fossil fragments include all shelly organic debris originally composed of $CaCO_3$ (in the form of calcite or a denser phase, aragonite). Carbonate pellets and rip-up clasts are small lumps of carbonate mud (a few millimeters in size) that have been consolidated either by being eaten and excreted (pellets), or by settling and then being ripped-up by wave energy (rip-up clasts). Ooids are sand-sized, concentrically layered grains that form by inorganic **precipitation** of calcium carbonate during agitation of seawater (usually by rolling on a shallow shoal **area** of the ocean).

The sediment precursor to limestone forms in the shallow marine realm or, less commonly, within carbonate-rich **lakes**. A special kind of marine limestone, composed entirely of the remains of marine micro-plankton, is called chalk. There is also a special kind of limestone, travertine, which forms from fresh-water deposition of dissolved carbonate within **cave** and cavern systems.

The original sediment determines limestone texture (i.e., the size and nature of grains in the rock). Micritic limestone is made of microcrystalline calcite like the original carbonate mud. Fossiliferous limestone is made of a large proportion of fossil fragments and the balance of the rock is either carbonate mud, carbonate cement (sparry calcite crystals between grains), or a mixture of both. Pelletal limestone and limestone with rip-up clasts is much like fossiliferous limestone regarding the balance of the rock (mud, spar, or both). Ooid limestone has a high proportion of ooid grains in it. Limestone that is made of sediment formed within or near organic reefs is sometimes referred to as reef rock or boundstone.

These hundred-ton haul trucks look like toys in this limestone quarry near St. Genevieve, Missouri. ***AP/Wide World. Reproduced by permission.***

Limestones contain extensive fossil records spanning much **geologic time**, including microfossils, megafossils, and trace **fossils** (or ichnofossils). Limestones are particularly common **sedimentary rocks**, representing times in Earth history when globally warm conditions prevailed along with particularly high sea levels. High sea levels during these times promoted development of extensive, shallow **seas** (i.e., epicontinental seas) across much of Earth's continental **space**. Epicontinental seas with extensive limestone deposits characterize the geological time intervals such as Late Cambrian-Ordovician, Mississippian, and Cretaceous.

Limestones are particularly susceptible to dissolution by acidic **groundwater**, and for this reason, extensive subterranean cave and cavern systems are known from within many limestone formations. The calcite in limestones is also susceptible to replacement by **dolomite** where the limestone meets magnesium-rich, briny groundwaters. Where this replacement is extensive, limestone formations are changed to dolostones by this process. Considerable **porosity** (approximately seven percent by volume) is created within the former limestone (now dolostone), and this pore space can host important hydrocarbon and mineral deposits. Limestone is also commonly replaced by **chert** in places where silica has been transported into the limestone by groundwaters.

Limestone is economically important as a source of quicklime (CaO), which can be produced by heating calcite to drive off **carbon dioxide** (CO_2). In addition to agricultural uses, limestone is used in cement making and as a flux in the smelting of **iron**. Limestone can be used also for road construction and as ornamental building stone.

LINEAL DUNES • *see* DUNES

LINEATION

A lineation is any linear feature or element in a **rock**, and can occur as the product of tectonic, mineralogical, sedimentary, or geomorphic processes. Lineations are the one-dimensional counterparts of foliations, and both are part of the fabric (geometric organization of features) of a rock. Lineations and foliations are said to possess preferred orientations, meaning that the spatial orientation of the features comprising the lineation or foliation is similar throughout the rock mass.

The spatial orientation of a lineation is described by two angles known as bearing and plunge. The plunge angle is the inclination of the lineation relative to an imaginary horizontal plane (ranging from 0 to 90 degrees), whereas the bearing angle is the compass direction of the lineation in the direction of the plunge (ranging from 0 to 360 degrees).

Structural lineations are those that are formed by tectonic activity such as folding, faulting, or **metamorphism**. Structural lineations can be either discrete or constructed. Discrete lineations are formed by the deformation and alignment of objects such as **fossils** or initially spherical pebbles. When a rock containing discrete objects (such as fossils or nearly spherical pebbles) is subjected to stress, the objects can be deformed into ellipsoids that share a preferred orientation throughout the rock. Constructed lineations are those that are formed during deformation and therefore do not involve preexisting objects. Constructed lineations include those formed by the intersections of two planes (e.g., the intersections some combination of foliations, fractures, or **bedding** planes) and slickenlines (also referred to as slickensides) along fault surfaces.

Mineral lineations are formed by the preferred orientation of either individual mineral grains or clusters of mineral grains. Mineral lineations can be formed by the nearly parallel alignment of mineral grains or clusters that have a needle like habit (e.g., amphiboles), by elongation of mineral grains or clusters during deformation, or by the preferentially oriented growth of **minerals** in response to the ambient state of stress during metamorphism. A mineral lineation formed by elongation of grains is similar to a discrete structural lineation.

Sedimentary lineations include pebbles aligned in the direction of stream flow and the crests of ripple marks. They are typically, although not exclusively, found on bedding planes in **sedimentary rocks**.

The slip surfaces of landslides can contain slickenlines similar to those found on fault surfaces, although they are generally considered to be of geomorphic rather than tectonic origin. Likewise, preferentially aligned clasts in sheared glacial **till** are similar to discrete structural lineations in tectonically deformed rocks, but most geologists do not consider them to be tectonic features.

See also Bedforms (ripples and dunes); Metamorphic rock; Shear zones

LINNÉ, CARL VON (1707-1778)

Swedish physician and botanist

Carl von Linné (Linnaeus) decisively broke through centuries of confusion over how to revise the classification system that had been in place since antiquity. With few parallels in the history of science, Linnaeus's contribution to botany will remain intact perhaps as long as the first classification system.

Linnaeus was born in Stenbrohult, Sweden. His father, a clergyman, maintained a small botanical garden on the parsonage grounds, where Linnaeus earned the nickname "little botanist." In 1716, Linnaeus entered a Latin school and began to formalize his interest in botany and the natural sciences. In 1727, he transferred to the University of Lund to study medicine, but he also undertook extensive botanical excursions. One year later, he went on to the University of Uppsala, which was considered a better school for medicine, but Linnaeus was disappointed to find that its facilities were no better than those at the University of Lund. Nevertheless, Uppsala did have something that made up for the shortcoming, a botanical garden containing rare foreign plants.

As his academic ideas started to mature along with his research, Linnaeus constructed a new theory of plant sexuality. In 1735, he published his *System Naturae*, and two years later, *Genera Planetarum*. He also moved briefly to Holland, where he received his M.D. In 1739, Linnaeus began to practice medicine, and two years later, he became the chair of botany, dietetics, and materia medica at the University of Uppsala. For the rest of his life, Linnaeus remained in this position, while his fame as a premier botanist spread throughout the world because of his influence in revising the 2,000-year-old system of classification.

The philosopher Aristotle had devised the first classification system over 2,000 years earlier, when he established the basic principles of dividing and subdividing plants and animals. At that time, only about a thousand species were known. Therefore, he grouped them into simple categories of animals with backbones and animals without backbones. Plants were divided into different categories that dealt more with size and appearance. By the sixteenth century, however, the system was proving to be less and less adequate as the body of knowledge of plants and animals grew. Modification came slowly, often marked with debate and controversy, succeeding only in revealing the complexity of the process. In 1753, Linnaeus published his *Species Planetarium*, in which he replaced the antiquated Aristotelian system with the principles of classification used today.

In creating his system, Linnaeus's primary consideration was the number of observable characteristics of the organism, specifically its anatomy, structures, and details of reproduction. Based on his observations, Linnaeus created a hierarchical system in which living things were grouped according to their similarities, with each succeeding level possessing a larger number of shared traits. He named these levels class, order, genus, and species.

Linnaeus also popularized binomial nomenclature, giving each living thing a Latin name consisting of its genus and species, which distinguished it from all other organisms. For example, the cougar received the scientific name *Felis concolor*, while the lion became *Panthera leo*. This system allowed scientists to communicate worldwide about organisms without having to understand different languages. Also, each type of organism can be fitted into the scheme in a logical and orderly manner, allowing for infinite expansion. The various hierarchical levels in the system provide as well a conceptual framework for understanding the relationships among different organisms or groups of organisms.

Linnaeus's desire to classify all living things often bordered on the compulsive; he believed his work to be divinely inspired and considered those who did not follow his system to be "heretics." However, he was also a skilled and caring instructor who nurtured the interests of his many students, often sending them abroad to the Middle East, China, and the Pacific Islands for new specimens. In 1761, Linnaeus was given the noble title von Linné, and while the king of Spain offered him generous compensation to settle in his country, Linnaeus remained in Sweden at Uppsala until his death after a stroke in 1778.

Today an international commission of scientists maintains the Linnaeus classification system and adheres to the rules for adopting scientific names when newly discovered species or subspecies need to be classified. Although the system depends on the judgments and opinions made by biologists, its concept and general organization are accepted by scientists throughout the world.

LIPPERSHEY, HANS (1570-1619)

German-born Dutch lens maker

Although there is some debate, most historians argue that Hans Lippershey was the first inventor of the **telescope**. Born in Wesel (Germany), Lippershey migrated to Zeeland in the Netherlands. Little is known about Lippershey's personal life except that he married in 1594 and officially became a citizen of his adopted country in 1602.

According to fragmented documentary evidence (including third party diary entries), Lippershey, an eyeglass maker, developed the idea for the telescope after watching two children in his eyeglass shop play with his lenses. The legend holds that children grasping two lenses and, looking through both simultaneously, noticed that a **weather** vane on a nearby church steeple seemed to appear larger and clearer than visible by normal sight. Lippershey realized the potential of this accidental discovery and proceeded to make a telescope by attaching lenses at the two ends of a tube.

Lippershey applied for a patent in 1608, but the device could not be kept a secret and the patent was eventually denied. Others came forth claiming to have invented the new device, including Jacob Metius and Sacharias Janssen, both of the Netherlands. Regardless, Lippershey's application for a patent remains the earliest record of a telescope, which he called a *kijker*, or "looker." Lippershey also benefited financially from his invention through the Dutch government, which paid him to construct several telescopes for military use.

See also Hubble Space Telescope (HST)

LITHIFICATION

When sediments are first deposited, they are unconsolidated and are not considered a **rock**. Lithification is the process of converting unconsolidated sediments into sedimentary rock. Lithification involves primarily the processes of compaction and cementation. Recrystallization is also an important process for some sediments.

Compaction is the rearrangement of sedimentary particles to reduce pore **space** and squeeze out pore **water**. Unlithified sediments generally contain some excess space between grains. This is especially true in the case of very fine-grained sediments such as **clay** and mud. Coarser grained sediments such as **sand** and gravels are heavy enough to settle with a minimum of pore space. Over time, as sediments accumulate in basins, the thickness and weight of the overlying sediments increases. The pressure on the buried sediments causes all the grains to compress together as tightly as possible. Excess interstitial water is also forced out and the sediments are now compacted.

The next step is cementation. Only after cementation has occurred can the sediments be considered a rock. Although compaction has reduced the pore space within sediments, some space remains. In addition, even though the sediments are compacted to a high degree and have been de-watered, the great pressures and higher temperatures in a sedimentary basin can force hot circulating waters, or basinal brines, to permeate through the sediments. These fluids have the ability to carry dissolved **minerals** and deposit them within the available pore space of sediments, binding them into rock.

The cement may be derived either from outside sediments or from within the sediments themselves. Externally sourced cementing material is dissolved from some other rock formation or sediments that the fluids permeated prior to entering the sediments to be cemented. Alternatively, a permeating fluid may dissolve the cementing mineral from within the sediments themselves and then redeposit them before exiting.

The most common cementing materials are calcium carbonate, silica, and **iron** oxides. Calcium carbonate cement is usually in the form of calcite. Silica cement is dominantly **quartz** but also can be **chert** or chalcedony. Iron oxide cements occur in the form of hematite or limonite.

Some sediments may become lithified by the recrystallization of mineral constituents rather than by cementation. This is an important process in the formation of **limestone** and some shales. As the name implies, it involves the *in situ* recrystallization of the sedimentary grains. In this process, minerals will recrystallize as a response to a change in their chemical environment, such as a rise in the **pH**. This is because some minerals are more stable than others are in a given set of conditions. Entire grains may reform, or just the rims of minerals. As mineral grains recrystallize, they grow together, forming new interlocking grain boundaries. These interlocking **crystals** bind the sediments into rock.

See also Sedimentary rocks; Sedimentation

LITHOPHILE • *see* CHALCOPHILES, LITHOPHILES, SIDEROPHILES, AND ATMOPHILES

LITHOSPHERE

The word lithosphere is derived from the word sphere, combined with the Greek word *lithos*, meaning **rock**. The lithosphere is the solid outer section of Earth, which includes Earth's **crust** (the "skin" of rock on the outer layer of planet Earth), as well as the underlying cool, dense, and rigid upper part of the upper mantle. The lithosphere extends from the surface of Earth to a depth of about 44–62 mi (70–100 km). This relatively cool and rigid section of Earth is believed to "float" on top of the warmer, non-rigid, and partially melted material directly below.

Earth is made up of several layers. The outermost layer is called Earth's crust. The thickness of the crust varies. Under the **oceans**, the crust is only about 3–5 mi (5–10 km) thick. Under the continents, however, the crust thickens to about 22 mi (35 km) and reaches depths of up to 37 mi (60 km) under some mountain ranges. Beneath the crust is a layer of rock material that is also solid, rigid, and relatively cool, but is assumed to be made up of denser material. This layer is called the upper part of the upper mantle, and varies in depth from about 31–62 mi (50–100 km) below Earth's surface. The combination of the crust and this upper part of the upper mantle, which are both comprised of relatively cool and rigid rock material, is called the lithosphere.

Below the lithosphere, the **temperature** is believed to reach 1,832°F (1,000°C), which is warm enough to allow rock material to flow if pressurized. Seismic evidence suggests that there is also some molten material at this depth (perhaps about 10%). This zone which lies directly below the lithosphere is called the **asthenosphere**, from the Greek word *asthenes*, meaning weak. The lithosphere, including both the solid portion of the upper mantle and Earth's crust, is carried "piggyback" on top of the weaker, less rigid asthenosphere, which seems to be in continual motion. This motion creates stress in the rigid rock layers above it, forcing the slabs or plates of the lithosphere to jostle against each other, much like **ice** cubes floating in a bowl of swirling **water**. This motion of the **lithospheric plates** is known as **plate tectonics**, and is responsible for many of the movements seen on Earth's surface today including earthquakes, certain types of volcanic activity, and continental drift.

See also Continental drift theory; Earth (planet); Earth, interior structure

LITHOSPHERIC PLATES

Lithospheric plates are regions of Earth's **crust** and upper mantle that are fractured into plates that move across a deeper plasticine mantle.

Earth's crust is fractured into 13 major and approximately 20 total lithospheric plates. Each lithospheric plate is composed of a layer of oceanic crust or continental crust superficial to an outer layer of the mantle. Containing both crust and the upper region of the mantle, lithospheric plates are generally considered to be approximately 60 mi (100 km) thick. Although containing only continental crust or oceanic crust in any one cross-section, lithospheric plates may contain various sections that exclusively contain either oceanic crust or continental crust and therefore lithospheric plates may contain various combinations of oceanic and continental crust. Lithospheric plates move on top of the **asthenosphere** (the outer plastically deforming region of Earth's mantle).

The term "plate" is deceptive. Remembering that Earth is an oblate sphere, lithospheric plates are not flat, but curved and fractured into curved sections akin to the peeled sections of an orange. Accordingly, analysis of lithospheric plate movements and dynamics requires more sophisticated mathematics that account for the curvature of the plates.

In geological terms, there are three types of boundaries between lithospheric plates. At divergent boundaries, lithospheric plates move apart and crust is created. At convergent boundaries, lithospheric plates move together in collision zones where crust is either destroyed by subduction or uplifted to form **mountain chains**. Lateral movements between lithospheric plates create **transform faults** at the sites of plate slippage.

At each of the unique lithospheric plate boundaries there are specific geophysical forces that are characteristic of the plate dynamics. At transform boundaries there are shearing forces between the lithospheric plates. At divergent boundaries, tensional forces dominate the interaction between plates.

At subduction sites, compression of lithospheric plate material dominates.

The dynamics of **plate tectonics**, driven by deeper thermal processes, stress and cause elastic strain on lithospheric materials. Resulting fractures of **rock** in the **lithosphere** cause a release of energy in the form of seismic waves (i.e. an **earthquake**).

Because Earth's diameter remains constant, there is no net creation or destruction of lithospheric plates.

In contrast to the technical definition of lithosphere used by geologists, many geographers use the term lithosphere to denote landmass. This is a distinct concept as the geological definition of lithosphere may include sections containing oceanic crust completely submerged beneath Earth's **oceans**. Using the geographical definition, Earth is approximately 71% hydrosphere (a region covered by **water**) and 21% lithosphere (a region of land).

See also Dating methods; Earth, interior structure; Hawaiian Island formation; Mantle plumes; Mapping techniques; Mid-ocean ridges and rifts; Mohorovicic discontinuity (Moho); Ocean trenches; Rifting and rift valleys; Subduction zone

LOESS • *see* DUNE FIELDS

LONGITUDE • *see* LATITUDE AND LONGITUDE

LONGSHORE DRIFT

Longshore drift is the transport of **sand** along a beach by waves impinging or breaking at an angle to the beach. Longshore drift occurs when a wave breaks, lifts sand into suspension, and then throws a pulse of sand-bearing **water** (swash) up the slope of the beach. If the wave breaks on the beach at an angle, the swash travels simultaneously up the beach and along the beach in the direction of the wave's original motion. Friction and **gravity** slow and halt the upward progress of the swash, and it begins to arc down the beach as backwash (still moving, though more slowly, along the beach). Suspended sand settles out of the backwash when it reaches the waterline and mixes with the relatively stationary water there.

Relative to the beach surface, the path of a typical grain of sand suspended by a breaking wave is therefore a lopsided parabola: up, over, and down. Some grains will be moved similarly by the next wave, or the next, again and again, and so are transported along the beach by steps.

Beaches are continually shaped and shifted by longshore drift. At Cape Cod, for example, long—approximately straight—wave-fronts from the east impinge on a bulging shoreline. Along the northern half of the Cape these westbound waves strike the beach at an angle that moves sand northward toward Provincetown. To the south, the same waves strike at angle that moves sand southward, toward the "elbow" of the Cape. In the last hundred years or so, consequently, the ends of the Cape have gained land while the central beach has receded.

Longshore drift is one of the few processes that can transport sand for long distances along a slope at a fixed altitude.

See also Beach and shoreline dynamics

LYELL, CHARLES (1797-1875)

Scottish geologist

Charles Lyell was a scientist whose ideas were important to the development of theories of geological and evolutionary change. Lyell's most influential textbook was *Principles of Geology*, published in 1833. Other well-known books written by Lyell are *Travels in North America, with Geological Observations* and *The Antiquity of Man*. Because of his great influence on the development of the principles of his discipline, Charles Lyell is sometimes referred to as a father of modern **geology** (along with another Scot, **James Hutton**, 1726–1797).

Lyell's most important theory, which built upon earlier work of Hutton, was the so-called theory of **uniformitarianism**, which largely refuted the previously widely believed doctrine of **catastrophism**.

According to the theory of uniformitarianism, major geological forces that are observed today also occurred in the past, and likely throughout the history of Earth. Examples of such forces include volcanism, earthquakes, and **erosion** by **wind**, **water**, and **gravity**. Moreover, the theory states that these existing causes have been responsible for major changes that have occurred in the structure of the earth during its geological history. A central element of the interpretation of the theory of uniformitarianism is the importance of time (over extremely long periods of time), even relatively slow-acting forces like erosion by wind and water can have an enormous influence on the character of Earth's surface.

Catastrophism is an earlier, very different doctrine that was widely believed by many scientists, but has largely been replaced by Lyell's (this kind of rapid change in scientific understanding is sometimes referred to as a "revolution"). According to catastrophism, major changes in Earth's structure, as implied by rapid changes in geological stratification and in fossil assemblages, were caused by sudden, violent, cataclysmic events, rather than by gradual, evolutionary and environmental changes. Before the influence of Lyell, most scientists and people of western culture believed that Earth and its species only had a history of about 6,000 years, based on a literal interpretation of the Book of Genesis in the *Bible*. However, the observations of Lyell and other geologists of his time were reporting clearly contradictory evidence about the forces influencing the geological character of Earth and the **evolution** of its existing species. These observations of the real, natural world suggested that life was much more ancient than only a few thousand years, and that existing species appeared to have evolved from previous ones, which are now extinct. These ideas of Lyell and his colleagues were extremely influential on other scientists, including Charles

Darwin (1809–1882), who is best known for his theory of the role of natural selection in driving evolutionary change, published in 1859 in his famous book, *On the Origin of Species*.

Another important concept championed by Lyell, also building upon previous work by James Hutton, was that older rocks were generally buried beneath younger ones. As such, careful excavation and studying of geological layers and the **fossils** they contain could be used to understand the geological and evolutionary history of Earth.

See also Evolution, evidence of; Evolutionary mechanisms; Fossil record; Geologic time; Solar system

WORLD *of* EARTH SCIENCE

WORLD *of* EARTH SCIENCE

K. Lee Lerner and Brenda Wilmoth Lerner, *Editors*

Volume 2

M-Z

GALE GROUP
THOMSON LEARNING™

Detroit • New York • San Diego • San Francisco
Boston • New Haven, Conn. • Waterville, Maine
London • Munich

THOMSON
GALE

World of Earth Science

K. Lee Lerner and Brenda Wilmoth Lerner

Project Editor
Ryan L. Thomason

Editorial
Deirdre S. Blanchfield, Madeline Harris, Kate Kretschmann, Michael D. Lesniak, Kimberley A. McGrath, Brigham Narins, Mark Springer

Permissions
Shalice Shah-Caldwell

Imaging and Multimedia
Robert Duncan, Leitha Etheridge-Sims, Lezlie Light, Kelly A. Quin, Barbara J. Yarrow

Product Design
Michael Logusz, Tracey Rowens

Manufacturing
Wendy Blurton, Evi Seoud

© 2003 by Gale. Gale is an imprint of The Gale Group, Inc., a division of Thomson Learning, Inc.

Gale and Design™ and Thomson Learning™ are trademarks used herein under license.

For more information contact
The Gale Group, Inc.
27500 Drake Rd.
Farmington Hills, MI 48331-3535
Or you can visit our Internet site at
http://www.gale.com

ALL RIGHTS RESERVED
No part of this work covered by the copyright hereon may be reproduced or used in any form or by any means—graphic, electronic, or mechanical, including photocopying, recording, taping, Web distribution, or information storage retrieval systems—without the written permission of the publisher.

For permission to use material from this product, submit your request via Web at http://www.gale-edit.com/permissions, or you may download our Permissions Request form and submit your request by fax or mail to:

The Gale Group, Inc.,
Permissions Department,
27500 Drake Road,
Farmington Hills, MI, 48331-3535,
Permissions hotline:
248-699-8074 or 800-877-4253, ext. 8006,
Fax: 248-699-8074 or 800-762-4058.

While every effort has been made to ensure the reliability of the information presented in this publication, The Gale Group, Inc. does not guarantee the accuracy of the data contained herein. The Gale Group, Inc. accepts no payment for listing; and inclusion in the publication of any organization, agency, institution, publication, service, or individual does not imply endorsement of the editors and publisher. Errors brought to the attention of the publisher and verified to the satisfaction of the publisher will be corrected in future editions.

ISBN 0-7876-7739-6 (set)
0-7876-7740-X (vol. 1)
0-7876-7741-8 (vol. 2)

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA

World of earth science / K. Lee Lerner and Brenda Wilmoth Lerner, editors.
p. cm.
Includes bibliographical references and index.
ISBN 0-7876-7739-6 (set)—ISBN 0-7876-7740-X (v. 1)—ISBN 0-7876-7741-8 (v. 2)
1. Earth sciences—Encyclopedias. I. Lerner, K. Lee. II. Lerner, Brenda Wilmoth.
QE5 .W59 2003
550'.3—dc21 2002012069

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

CONTENTS

H

I

J

K

L

P

Q

R

S

T

U

V

INTRODUCTION

As of June 2002, astronomers had discovered more than 100 other planets orbiting distant suns. With advances in technology, that number will surely increase during the opening decades of the twenty-first century. Although our explorations of the Cosmos hold great promise of future discoveries, among all of the known worlds, Earth remains unique. Thus far it is the only known planet with blue skies, warm seas, and life. Earth is our most tangible and insightful laboratory, and the study of Earth science offers us precious opportunities to discover many of the most fundamental laws of the Universe.

Although Earth is billions of years old, geology—literally meaning the study of Earth—is a relatively new science, having grown from seeds of natural science and natural history planted during the Enlightenment era of the eighteenth and nineteenth centuries. In 1807, the founding of the Geological Society of London, the first learned society devoted to geology, marked an important turning point for the science (some say its nascence). In the beginning, geologic studies were mainly confined to the study of minerals (mineralogy), strata (stratigraphy), and fossils (paleontology), and hotly debated issues of the day included how well new geologic findings fit into religious models of creation. In less than two centuries, geology has matured to embrace the most fundamental theories of physics and chemistry—and broadened in scope to include the diverse array of subdisciplines that comprise modern Earth science.

Modern geology includes studies in seismology (earthquake studies), volcanology, energy resources exploration and development, tectonics (structural and mountain building studies), hydrology and hydrogeology (water-resources studies), geologic mapping, economic geology (e.g., mining), paleontology (ancient life studies), soil science, historical geology and stratigraphy, geological archaeology, glaciology, modern and ancient climate and ocean studies, atmospheric sciences, planetary geology, engineering geology, and many other subfields. Although some scholars have traditionally attempted to compartmentalize geological sciences into subdisciplines, the modern trend is to incorporate a holistic view of broader Earth science issues. The incorporation of once-diverse fields adds strength and additional relevance to geoscience studies.

World of Earth Science is a collection of 650 entries on topics covering a diversity of geoscience related interests—from biographies of the pioneers of Earth science to explanations of the latest developments and advances in research. Despite the complexities of terminology and advanced knowledge of mathematics needed to fully explore some of the topics (e.g., seismology data interpretation), every effort has been made to set forth entries in everyday language and to provide accurate and generous explanations of the most important terms. The editors intend *World of Earth Science* for a wide range of readers. Accordingly, *World of Earth Science* articles are designed to instruct, challenge, and excite less experienced students, while providing a solid foundation and reference for more advanced students.

World of Earth Science has attempted to incorporate references and basic explanations of the latest findings and applications. Although certainly not a substitute for in-depth study of important topics, we hope to provide students and readers with the basic information and insights that will enable a greater understanding of the news and stimulate critical thinking regarding current events (e.g., the ongoing controversy over the storage of radioactive waste) that are relevant to the geosciences.

The broader and intellectually diverse concept of Earth science allows scientists to utilize concepts, techniques, and modes of thought developed for one area of the science, in the quest to solve problems in other areas. Further, many geological problems are interrelated and a full exploration of a particular phenomenon or problem demands overlap between subdisciplines. For this reason, many curricula in geological sciences at universities stress a broad geologic education to prepare graduates for the working world, where they may be called upon to solve many different sorts of problems.

World of Earth Science is devoted to capturing that sense of intellectual diversity. True to the modern concept of Earth science, we have deliberately attempted to include some of the most essential concepts to understanding Earth as a dynamic body traveling through space and time.

Although no encyclopedic guide to concepts, theories, discoveries, pioneers, issues and ethics related to Earth science could hope to do justice to any one of those disciplines in two volumes, we have attempted to put together a coherent collection of topics that will serve not only to ground students in the essential concepts, but also to spur interest in the many diverse areas of this increasing critical set of studies.

In addition to topics related to traditional geology and meteorology, we have attempted to include essential concepts in physics, chemistry, and astronomy. We have also attempted to include topical articles on the latest global positioning (GPS), measurement technologies, ethical, legal, and social issues and topics of interest to a wide audience. Lastly, we have attempted to integrate and relate topics to the intercomplexities of economics and geopolitical issues.

Such a multifaceted and "real world" approach to the geosciences is increasingly in demand. In the recent past, geologic employment was dominated by the petroleum industry and related geologic service companies. In the modern world, this is no longer so. Mining and other economic geology occupations (e.g., prospecting and exploration), in former days plentiful, have also fallen away as major employers. Environmental geology, engineering geology, and ground water related jobs are more common employment opportunities today. As these fields are modern growth areas with vast potential, this trend will likely hold true well into the future. Many modern laws and regulations require that licensed, professional geologists supervise all or part of key tasks in certain areas of engineering geologic work and environmental work. It is common for professional geologists and professional engineers to work together on such projects, including construction site preparation, waste disposal, ground-water development, engineering planning, and highway construction. Many federal, state, and local agencies employ geologists, and there are geologists as researchers and teachers in most academic institutions of higher education.

Appropriate to the diversity of Earth science, we attempted to give special attention to the contributions by women and scientists of diverse ethnic and cultural backgrounds. In addition, we have included special articles written by respected experts that are specifically intended to make *World of Earth Science* more relevant to those with a general interest in the historical and/or geopolitical topics aspects of Earth science.

The demands of a dynamic science and the urgency of many questions related to topics such as pollution, global warming, and ozone depletion place heightened demands on both general and professional students of geosciences to increasingly broaden the scope and application of their knowledge.

For example, geological investigations of ancient and modern disasters and potential disasters are important—and often contentious—topics of research and debate among geologists today. Among the focus areas for these studies are earthquake seismicity studies. While much work continues in well-known problem areas like southern California, Mexico City, and Japan, less well-known, but potentially equally dangerous earthquake zones like the one centered near New Madrid, Missouri (not far from Memphis, Tennessee and St. Louis, Missouri) now receive significnt research attention. Geologists cannot prevent earthquakes, but studies can help predict earthquake events and help in planning the design of earthquake-survivable structures. Another focus of study is upon Earth's volcanoes and how people may learn to live and work around them. Some volcanoes are so dangerous that no one should live near them, but others are more predictable. Earthquake prediction and planning for eruptions is going on today by looking at the geologic record of past eruptions and by modern volcano monitoring using thermal imaging and tilt or motion-measuring devices. Other foci of disaster prevention research include river-flood studies, studies of slope stability (prevention of mass movement landslides), seismic sea-wave (tsunami) studies, and studies of possible asteroid or comet impacts.

Aside from geologic studies of disaster, there is a side of geology centered upon providing for human day-to-day needs. Hydrology is an interdisciplinary field within geology that studies the relationship of water, the earth, and living things. A related area, hydrogeology, the study of ground water, has undergone a revolution recently in the use of computer modeling to help understand flow paths and characteristics. These studies of water flow on the surface and in the subsurface connect with other subdisciplines of geology, such as geomorphology (the study of landforms, many of which are formed by water flow), river hydrology, limnology (study of lakes), cave and sinkhole (karst) geology, geothermal energy, etc. Geologic studies related to human and animal health (i.e., medical geology) are becoming very common today. For example, much work is currently devoted to tracing sources of toxic elements like arsenic, radon, and mercury in rock, soil, air, water, and groundwater in many countries, including the United States. There has been a major effort on the part of medical geologists to track down dangerous mineral species of asbestos (not all asbestos is harmful) and determine how best to isolate or remove the material. Atmospheric scientists have been at work for some years on the issue of air-born pathogens, which ride across oceans and continents born on fine soil particles lifted by winds.

Geologists are also focused on study of the past. Today, paleobotany and palynology (study of fossil spores and pollen) complement traditional areas of invertebrate and vertebrate paleontogy. Recent discoveries such as small, feathered dinosaurs and snakes with short legs are helping fill in the ever-shrinking gaps within the fossil record of evolution of life on Earth. Paleontologic studies of extinction, combined with evidence of extraterrestrial bombardment, suggest that mass death and extinction of species on Earth at times in the past has come to us from the sky. In a slightly related area, geoarchaeology, the geologic context of archaeological remains and the geologic nature of archaeological artifacts remains key to interpreting details about the pre-historic human past. Careful study of drilling records of polar ice sheets, deep-sea sediments, and deep lake sediments has recently revealed that many factors, including subtle variations in some of Earth's orbital parameters (tilt, wobble, and shape of orbit around the Sun), has had a profound, cyclical effect upon Earth's climate in the past (and is continuing today). Paleontologic studies, combined with geologic investigations on temperature sensitive ratios of certain isotopes (e.g. O^{16}/O^{18}), have helped unlock mysteries of climate change on Earth (i.e., the greenhouse to icehouse vacillation through time).

Earth science studies are, for the first time, strongly focused on extraterrestrial objects as well. Voyages of modern exploratory spacecraft missions to the inner and outer planets have sent back a wealth of images and data from the eight major planets and many of their satellites. This has allowed a new field, planetary geology, to take root. The planetary geologist is engaged in photo-geologic interpretation of the origin of surface features and their chronology. Planetary geologic studies have revealed some important comparisons and contrasts with Earth. We know, for example, some events that affected our entire solar system, while the effects of other events were unique to certain planets and satellites. In addition, planetary geologists have found that impact-crater density is important for determining relative age on many planets and satellites. As a result, Earth is no longer the only planet with a knowable geologic time scale.

The geosciences have undergone recent revolutions in thought that have profoundly influenced and advanced human understanding of Earth. Akin to the fundamental and seminal concepts of cosmology and nucleosynthesis, beginning during the 1960s and continuing today, the concept of plate tectonics has revolutionized geologic thought and interpretation. Plate tectonics, the concept that the rigid outer part of Earth's crust is subdivided into plates, which move about on the surface (and have moved about on the surface for much of geologic time) has some profound implications for all of geology. This concept helps explain former mysteries about the distribution of volcanoes, earthquakes, and mountain chains. Plate tectonics also helps us understand the distribution of rocks and sediments on the sea floor, and the disparity in ages between continents and ocean floors. Plate motion, which has been documented through geologic time, helps paleontologists explain the distribution of many fossil species and characteristics of their ancient climates. Plate tectonic discoveries have caused a rewriting of historical geology textbooks in recent years.

Although other volumes are chartered to specifically explore ecology related issues, the topics included in *World of Earth Science* were selected to provide a solid geophysical foundation for ecological or biodiversity studies. We have specifically included a few revolutionary and controversial concepts, first written about in a comprehensive way during the 1970s, such as the Gaia hypothesis. Simply put, Gaia is the notion that all Earth systems are interrelated and interconnected so that a change in one system changes others. It also holds the view that Earth functions like a living thing. Gaia, which is really a common-sense philosophic approach to holistic Earth science, is at the heart of the modern environmental movement, of which geology plays a key part.

Because Earth is our only home, geoscience studies relating meteor impacts and mass extinction offer a profound insight into delicate balance and the tenuousness of life. As Carl Sagan wrote in *Pale Blue Dot: A Vision of the Human Future in Space*, "The Earth is a very small stage in a vast cosmic arena." For humans to play wisely upon that stage, to secure a future for the children who shall inherit Earth, we owe it to ourselves to become players of many parts, so that our repertoire of scientific knowledge enables us to use reason and intellect in our civic debates, and to understand the complex harmonies of Earth.

K. Lee Lerner & Brenda Wilmoth Lerner, editors
London
May, 2002

How to Use the Book

The articles in the book are meant to be understandable by anyone with a curiosity and willingness to explore topics in Earth science. Cross-references to related articles, definitions, and biographies in this collection are indicated by **bold-faced type**, and these cross-references will help explain, expand, and enrich the individual entries.

This first edition of *World of Earth Science* has been designed with ready reference in mind:

- **Entries are arranged alphabetically**, rather than by chronology or scientific field.
- **Bold-faced terms** direct reader to related entries.
- **"See also" references** at the end of entries alert the reader to related entries not specifically mentioned in the body of the text.
- A **Sources Consulted** section lists the most worthwhile print material and web sites we encountered in the compilation of this volume. It is there for the inspired reader who wants more information on the people and discoveries covered in this volume.
- The **Historical Chronology** includes many of the significant events in the advancement of the diverse disciplines of Earth science. The most current entries date from just days before *World of Earth Science* went to press.
- A **comprehensive General Index** guides the reader to topics and persons mentioned in the book. Bolded page references refer the reader to the term's full entry.

A detailed understanding of physics and chemistry is neither assumed nor required for *World of Earth Science*. In preparing this text, the editors have attempted to minimize the incorporation of mathematical formulas and to relate physics concepts in non-mathematical language. Accordingly, students and other readers should not be intimidated or deterred by chemical nomenclature. Where necessary, sufficient information regarding atomic or chemical structure is provided. If desired, more information can easily be obtained from any basic physics or chemistry textbook.

For those readers interested in more information regarding physics related topics, the editors recommend Gale's *World of Physics* as an accompanying reference. For those readers interested in a more comprehensive treatment of chemistry, the editors recommend Gale's *World of Chemistry*.

In an attempt to be responsive to advisor's requests and to conform to standard usage within the geoscience community, the editors elected to make an exception to previously used style guidelines regarding geologic time. We specifically adopted the convention to capitalize applicable eons, eras, periods and epochs. For example, Cenozoic Era, Tertiary Period, and Paleocene Epoch are intentionally capitalized.

Advisory Board

In compiling this edition, we have been fortunate in being able to rely upon the expertise and contributions of the following scholars who served as academic and contributing advisors for *World of Earth Science*, and to them we would like to express our sincere appreciation for their efforts to ensure that *World of Earth Science* contains the most accurate and timely information possible:

Cynthia V. Burek, Ph.D.
Environment Research Group, Biology Department
Chester College, England, U.K.

Nicholas Dittert, Ph.D.
Institut Universitaire Européen de la Mer
University of Western Brittany, France

William J. Engle. P.E.
Exxon-Mobil Oil Corporation (Rt.)
New Orleans, Louisiana

G. Thomas Farmer, Ph.D., R.G.
Earth & Environmental Sciences Division,
Los Alamos National Laboratory
Los Alamos, New Mexico

Lyal Harris, Ph.D.
Tectonics Special Research Center, Dept. of Geology & Geophysics
University of Western Australia
Perth, Australia

Alexander I. Ioffe, Ph.D.
Senior Scientist, Geological Institute of the Russian Academy of Sciences
Moscow, Russia

David T. King, Jr., Ph.D.
Professor, Dept. of Geology
Auburn University
Auburn, Alabama

Cherry Lewis, Ph.D.
Research Publicity Officer
University of Bristol
Bristol, England, U.K.

Eric v.d. Luft, Ph.D., M.L.S.
Curator of Historical Collections
S.U.N.Y. Upstate Medical University
Syracuse, New York

Jascha Polet, Ph.D.
Research Seismologist, Caltech Seismological Laboratory,
California Institute of Technology
Pasadena, California

Yavor Shopov, Ph.D.
Professor of Geology & Geophysics
University of Sofia
Sofia, Bulgaria

Acknowledgments

In addition to our advisors and contributing advisors, it has been our privilege and honor to work with the following contributing writers and scientists who represent scholarship in the geosciences that spans five continents:

Molly Bell, Ph.D.; Alicia Cafferty; John Cubit, Ph.D.; Laurie Duncan, Ph.D.; John Engle; Agnes Galambosi; Larry Gilman, Ph.D.; David Goings, Ph.D.; Brooke Hall, Ph.D.; William Haneberg, Ph.D.; Michael Lambert; Adrienne Wilmoth Lerner, (Graduate Student, Department of History, Vanderbilt University), Lee Wilmoth Lerner, Jill Liske, M.Ed.; Robert Mahin, Ph.D.; Kelli Miller; William Phillips, Ph.D.; William Rizer, Ph.D.; Jerry Salvadore, Ph.D.; and David Tulloch, Ph.D.

Many of the academic advisors for *World of Earth Science*, along with others, authored specially commissioned articles within their field of expertise. The editors would like to specifically acknowledge the following special contributions:

Cynthia V. Burek, Ph.D.
History of geoscience: Women in the history of geoscience

Nicholas Dittert, Ph.D.
Scientific data management in Earth sciences

William J. Engle. P.E.
Petroleum, economic uses of
Petroleum extraction

G. Thomas Farmer, Ph.D., R.G.
Hydrogeology

Lyal Harris, Ph.D.
Supercontinents

Alexander I. Ioffe, Ph.D.
Bathymetric mapping

David T. King, Jr., Ph.D.
Geologic time
Stratigraphy
Uniformitarianism

Cherry Lewis, Ph.D.
The biography of Author Holmes

Yavor Shopov, Ph.D.
Paleoclimate

The editors wish to gratefully acknowledge Dr. Eric v.d. Luft for his diligent and extensive research related to his compilation of selected biographies for *World of Earth Science*.

The editors also gratefully acknowledge Dr. Yavor Shopov's generous and significant contribution of photographs for *World of Earth Science* and Dr. David King's guidance, comments, and contributions to the introduction.

The editors thank Ms. Kelly Quin and others representing the Gale Imaging Team for their guidance through the complexities and difficulties related to graphics. Last, but certainly not least, the editors thank Mr. Ryan Thomason, whose dedication, energy, and enthusiasm made a substantial difference in the quality of *World of Earth Science*.

Because Earth is theirs to inherit, the editors lovingly dedicate this book to their children, Adrienne, Lee, Amanda, and Adeline. *Per ardua ad astra.*

Cover

The image on the cover depicts an example of several geologic cross sections of strata, illustrating the fundamental laws of geology.

M

MACH SCALE • *see* SOUND TRANSMISSION

MAFIC

Igneous rocks are classified by geologists using various schemes. One of the several schemes based on chemical composition divides igneous rocks into four categories according to silica (**silicon** dioxide, SiO_2) content: (1) Rocks containing more than 66% silica are **silicic**. (2) Rocks containing 52–66% silica are classified as intermediate. (3) Rocks containing 45–52% silica are mafic. (4) Rocks containing less than 45% silica are ultramafic. The term acidic is sometimes used as a synonym for silicic and the terms basic and ferromagnesian as synonyms for mafic. Mafic is an invented adjective based on the chemical symbols for magnesium (Ma) and **iron** (Fe): Ma-Fe-ic, mafic. Mafic is sometimes used as a synonym for "dark-colored" when discussing the appearance of **minerals**.

Some mafic and ultramafic rocks are found on Earth's surface. However, because magnesium and iron are denser than silica, mafic rocks are denser than silicic rocks and tend to sink below them. This density difference explains the dependence of Earth's composition on depth. Earth's core consists mostly of fairly pure metal (iron and nickel); surrounding the core is the mantle, a layer consisting mostly of ultramafic **rock** (**metals** mixed with silica). The outermost layer of the earth, the **crust**, consists of two basic types of crust, one primarily mafic (oceanic crust) and the other primarily silicic (continental crust). Oceanic crust, which is only about 4 miles (6 km) thick, consists mostly of **basalt**, a mafic rock. As oceanic crust inches away from its point of origin at a mid-ocean ridge, its underside cools the ultramafic mantle rocks over which it slides. These cooled mantle rocks stick to the underside of the oceanic crust, thickening it over time. The oceanic crust is thus weighed down by an increasingly thick undercoating of cooled ultramafic mantle rock as it ages. This cool undercoating is denser than the chemically identical but hotter mantle rocks below. Eventually it becomes heavy enough to drag the oceanic crust right down into the mantle, as occurs at a spontaneous **subduction zone**. The continents, in contrast, are silicic, and float permanently on the mantle. Mafic oceanic crust is spontaneously subducted into the mantle after at most 200 million years, while the continents have never been subducted in the three or four billion years since they were formed.

By weight, Earth consists mostly of mafic and ultramafic rocks, but silicic rocks are far more abundant on Earth's surface. Mafic rocks commonly found on the surface include basalt, pyroxene, and biotite; common ultramafic rocks are dunite and **peridotite**

See also Earth, interior structure; Felsic; Sea-floor spreading

MAGELLAN, FERDINAND (1480-1521)

Portuguese mariner, explorer

Ferdinand Magellan was the first explorer to lead an expedition that circumnavigated the globe. Like many of his contemporaries, Magellan underestimated the size of the **oceans**, and thought he could find a faster route to the Spice Islands by sailing west. He began his voyage in September of 1519 with five ships. After an arduous voyage, only one ship returned. Magellan, the expedition leader, was not onboard.

Magellan was born in Portugal in 1480. His parents were low-ranking nobles, active in the Portuguese royal court. Through his education at court, Magellan learned navigation. He attained the rank of squire while in royal service as a merchant marine clerk. He joined Francisco de Almeida's voyages to explore the eastern coast of **Africa** in 1505 and 1506. By 1509, Magellan had traveled to Africa, Turkey, and India. In 1511, Magellan ventured to the Far East on a Portuguese expedition to Malaysia. Magellan returned to **Europe** but, soon after arriving home, then departed to fight for Portuguese interests in Morocco. He was wounded, and left the royal service soon after. He then turned his attention to gaining a charter for a fleet of his own, in hopes of returning to the Far East. In 1517, he began lobbying the Portuguese crown to fund a large expedition. He was denied a ship from the Portuguese crown, and then turned to the rival king of Spain.

Interested in Magellan's proposal to find a faster shipping route to the Far East, the Spanish king granted Magellan abundant funds. With the money, Magellan purchased five ships: the *Conception*, the *Santiago*, the *San Antonio*, the *Trinidad*, and the *Victoria*. The fleet left harbor in September of 1519 with 275 men and adequate provisions for only a few months.

From the start of the voyage, Magellan's fleet was plagued by problems. Magellan himself was Portuguese, but he was sailing under the Spanish flag. The rival nations were competing for trade routes and land in the New World, as well as for control of the **seas** in general. Thus, Magellan needed to avoid armed Portuguese ships, as well as Portuguese controlled ports in the New World. This limited the places where Magellan and his crew could stop to restock provisions, and made them wary of crossing Portuguese trade routes.

Magellan's Spanish captains, who sailed the other four ships, threatened his command of the fleet. On November 20, 1519, when a plot to mutiny against Magellan, organized by the captain of the *San Antonio*, Juan de Cartegena, was discovered, Cartegena was relieved of his command and imprisoned aboard the *Victoria*.

When Magellan set forth to discover an expedient trade route to the Spice Islands, he knew he would have to either find a passage through the New World, or sail around it. However, Magellan made two fatal miscalculations. He thought that both the New World (the landmass of the Americas) and the Pacific Ocean were much smaller than they actually are. The crew did not have adequate supplies, and had to make frequent stops to restock provisions on the ships. They spent several months on the open seas, and many sailors fell victim to scurvy, typhus, and various fevers. The extended duration of the voyage, coupled with the appalling conditions onboard, further disposed the crew against Magellan.

The voyage itself was arduous. Magellan did not reach the coast of Brazil until the December of 1519. He anchored off of the Portuguese port of Rio de Janeiro, but because of hostile relations between Spain and Portugal, kept most of the men onboard the ships. The fleet then sailed along the coast of **South America** looking for an inland passage, but as the **weather** grew colder and seas rougher, the fleet anchored and wintered in Patagonia (present-day southern Argentina). While in Patagonia, another mutiny was attempted. As an attempt to quell dissent in the fleet, Magellan executed some rebels and marooned the leaders of the insurrection when the fleet departed. Magellan sent the *Santiago* ahead to scout for a passage through the continent, but the ship sank in rough seas. Soon after, the remainders of the fleet departed to look for a passage to the Pacific. They arrived at the southern tip of South America in October. Magellan named the connecting waters the Strait of All Saints, but the strait now bears his name. Frightened of a longer and more grueling voyage ahead, the captain of the *San Antonio* turned his boat and sailed back towards Spain.

The remaining three ships reached the Pacific, but there were no navigational charts of the entire ocean. Magellan assumed the ocean was rather small, and predicted that the journey to the Spice Islands would take little more than a week. After three months, the crew reached the island of Guam. Without the food stores that were aboard the *San Antonio*, the remaining sailors lived off of rats, hard tack, sawdust, and any fish they could catch. Magellan anchored in Guam for several weeks to let his beleaguered crew recover. The crew then continued on to the Philippines. There, Magellan established good relations with the local king, but he and his men became involved in a tribal dispute. Several men were wounded and killed in the fighting, including Magellan. He died on April 27, 1521.

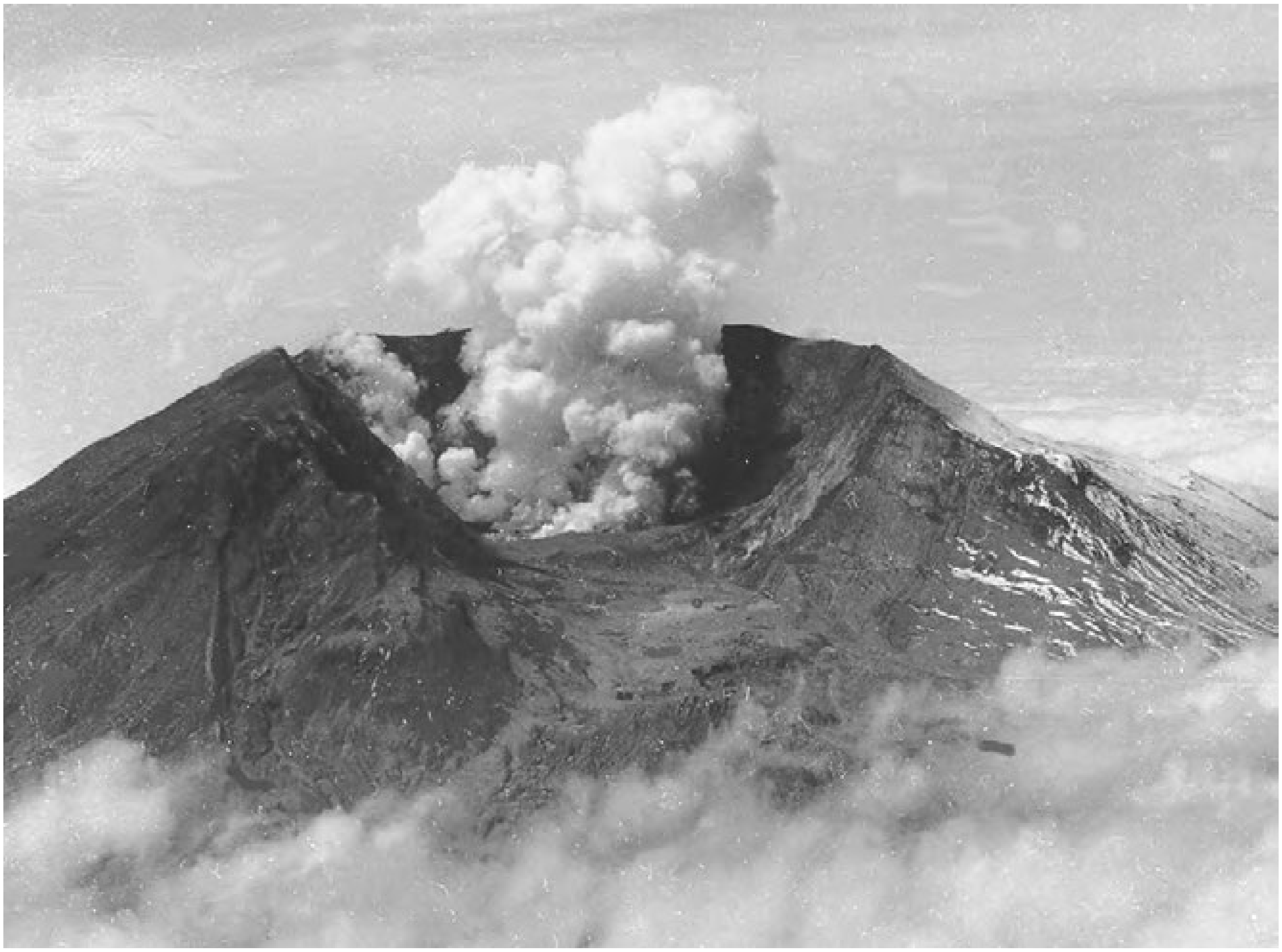
Though Magellan never fully circumnavigated the globe himself, the expedition he began did accomplish that monumental task. Stripped of her crew, the *Conception* was intentionally burned. The surviving 120 men of Magellan's crew, in two ships, departed the Philippines in May. Sebastian del Cano assumed control over the expedition. The two vessels reached the Spice Islands. Cano decided that the chances of one ship making it back to Spain were greater if the boats took different routes. Carrying a full hull of valuable cargo, the *Trinidad* sailed east, and the *Victoria* continued westward. The *Trinidad* was captured by the Portuguese, but the *Victoria* returned to Spain, with only 18 crewmembers left. Magellan's flagship was the first to circumnavigate the earth.

See also History of exploration II (Age of exploration); Oceans and seas

MAGMA

In **geology**, magma refers to molten **rock** deep within Earth that consists of liquids, gases, and particles of rocks and **crystals**. Magma has been observed in the form of hot **lava** and the various rocks made from the solidification of magma. Geologists have created magmas (artificial melts) in the laboratory to learn more about the physical conditions in which magma originated and its composition. Magma is the source of **igneous rocks**; it can intrude or force itself into surrounding rock where it cools and eventually hardens. These rocks are called intrusive igneous rocks. If magma rises all the way to Earth's surface it will extrude (push out), flowing or erupting out at the surface as lava, forming extrusive igneous rock (also called volcanic rock). Magma and the rocks it creates have similar chemical compositions.

Magma is generated within Earth's mantle, the thick layer between Earth's **crust** and outer core. Rock found deep within the crust is extremely hot, soft, and pliable, but rock does not become liquid until much deeper in the upper mantle. Pockets, or chambers of magma, can originate at various depths within the earth. The composition of the magma varies and indicates the source materials and depth from which they originated. **Silicon** dioxide (SiO_2) is the predominant ingredi-



The magma chamber inside Mt. St. Helens has gradually produced this lava dome inside the caldera of the volcano. In time, the volcano will erupt again in a violent explosion as the pressure within the magma chamber becomes too great to be contained. ***AP/Wide World. Reproduced by permission.***

ent in magma. Other ingredients include **aluminum** oxide, **iron**, magnesium, calcium, sodium, potassium, titanium, manganese, phosphorus, and **water**.

There are three basic types of magma, each having a characteristic origin and composition: basaltic (the most common, originating in the lower crust/upper mantle), rhyolitic (originates in the oceanic crust), and andesitic (most originate in the continental crust). New magma is formed by rocks **melting** when they sink deep into the mantle at subduction zones. The chemical composition, **temperature**, and the amount of dissolved liquids and gases determine the viscosity of magma. The more fluid a lava mixture is, the lower the viscosity. As magma or a lava flow cools, the mixture becomes more viscous, making it move slowly. Magmas having a higher silica (SiO_2) content are very viscous and move very slowly.

Magma has the tendency to rise because it weighs less than surrounding hard rock (liquids are less dense than solids) and because of the pressure caused by extreme temperature. The pressure is reduced as magma rises toward the surface. Dissolved gases come out of solution and form bubbles. The bubbles expand, making the magma even less dense, causing the magma to rise faster. The magma exerts a great deal of pressure on weak spots and fills up any cracks produced by the continual shifting of the earth’s crust. On its way up toward the surface, magma can melt adjacent rock, which provides a suitable environment for the development of metamorphic rocks. When magma erupts as lava, its gases are released at the surface into the atmosphere or can be trapped in the molten rock and cause “air bubbles” in rock. The gases can also create violent explosions, throwing debris for miles around.

See also Volcanic eruptions; Volcanic vent

MAGMA CHAMBER

A **magma** chamber is a reservoir of molten **rock** that is the source of **lava** in a volcanic eruption. Magma chambers are typically located a few kilometers below the surface. A magma chamber is created by a mantle plume, or upwelling of heat from the earth's mantle. This delivers heat and molten rock upwards to the base of the **crust**. Because magma is less dense than solid rock, it will rise through fractures. Dissolved gases under pressure also help to force the magma upwards. If the migrating magma can no longer find a path upwards, it may gather into a reservoir and form a magma chamber. Continual migration of more magma into the chamber will cause the pressure within the chamber to increase. At some point, the magma chamber may not be able to contain the pressure and the magma, and it may breech. The magma is then driven upward through a conduit such as a volcanic neck or **fissure**, resulting in the eruption of the **volcano**.

Sometimes, a magma chamber will experience a cessation in the influx of magma before it is able to release into a volcanic eruption. It this case, the magma may begin to cool and crystallize in place. As it does so, mineral **crystals** form and settle to the bottom while the remaining magma, depleted of the components that formed the initial **minerals**, pools at the top. Certain minerals will form first according to **Bowen's reaction series**, with crystallization becoming successively more silica rich. This process is known as fractional crystallization and results in a stratified igneous body, known as a layered intrusion. The Skaergaard intrusion in Greenland is a well known layered intrusion.

See also Volcanic eruptions

MAGNETIC FIELD

Earth acts as though it were a huge dipole magnet with the positive and negative poles near the North and South Poles. This does not mean that Earth is literally a dipole magnet—there are too many variations in the field—but that the best fit for a model of the field is two poles of a magnet, rather than a quadrupole, or other shape. The magnetic field of the earth allows magnetic compasses to work, making navigation much easier. It also molds the configuration of Van Allen belts, bands of high-energy charged particles around the earth's atmosphere.

Most of Earth's magnetic field (90%) occurs below the surface and possibly exists because Earth's core doesn't move at the same rate as the earth's mantle (the layer between the earth's core and its **crust**). The external 10% of the field is generated by movement of ions in the upper atmosphere.

The earth's magnetic field may help some animals navigate as they migrate. People have been using magnetic compasses for navigation since the fifteenth century. Because it has been so important for navigation, the magnetic field has been mapped all over the surface of the earth.

The magnetic field can also be used in other ways. For example, an instrument called a geomagnetic electrokinetograph determines the direction and speed of ocean currents while a ship is moving by measuring the voltage induced in the moving conductive sea **water** by the magnetic field of the earth.

The earth's magnetic field can change quickly and temporarily or slowly and permanently, depending on the cause of the change. The magnetic field can change very quickly, within an hour, in **magnetic storms**. These occur when the magnetic field is disturbed by sunspots, which send **clouds** of charged particles into Earth's atmosphere. (These same protons and electrons excite **oxygen**, nitrogen, and hydrogen atoms in the upper atmosphere, causing the **aurora borealis** and aurora australis.) These disturbances can be measured all over the globe and can cause static on radio stations.

The orientation of the magnetic field also changes slowly over centuries. In the planet's lifetime, the magnetic field has changed and even reversed (north pole becomes south and vice-versa) several times. Evidence for this is seen in reversed paleomagnetism of some sedimentary and igneous **rock**. In the 1960s, scientists showed that rocks formed at a particular interval in **geologic time** all indicate a magnetic field with the same orientation; older or younger rocks may show a reversed orientation. The cause of these paleomagnetic reversals is not yet known.

Today, the magnetic poles are not at the same place as the poles of the earth's rotational axis. Therefore, "magnetic north" is not quite the direction of "true north." The difference is known as the magnetic declination. Accordingly, scientists have established a series of geomagnetic coordinates, including **latitude and longitude**. These are centered on the magnetic dipole of the earth and designed (like geographic **latitude** and **longitude**) as though the earth were a perfect sphere.

See also Earth, interior structure; Earth (planet); Polar axis and tilt

MAGNETIC STORM • *see* CORONAL EJECTIONS AND MAGNETIC STORMS

MAGNETISM AND MAGNETIC PROPERTIES

Magnetism is a property of matter and it occurs in different forms and degrees in various Earth materials that act as conductors and insulators. For example, at low temperatures, metallic systems exhibit either superconducting or magnetic order. The degree of magnetism of a substance is due to the intrinsic magnetic dipole moment of its electrons. The degree of magnetism is also called magnetization and it is defined as the net magnetic dipole moment of the substance per unit volume.

In the nineteenth century, **Michael Faraday** was the first to start classifying substances according to their magnetic properties. Faraday classified them as either diamagnetic or paramagnetic and he based his classification on the force exerted on the materials when placed in an inhomogeneous **magnetic field**.

Diamagnetic substances have a negative magnetic susceptibility, (i.e., they are materials in which the magnetization and magnetic field are opposite). The electrons in the atoms of diamagnetic materials are all paired and there is no intrinsic magnetic moment. When a material is placed into a magnetic field its atoms acquire an induced magnetic moment pointing in a direction opposite to that of the external field and the material becomes magnetic.

The diamagnetic field produced opposes the external field, although this diamagnetic field is very weak (except in superconductors). If the atoms of a material have no magnetic moment of their own, then diamagnetism is the only magnetic property of the material and the material is called diamagnetic. Copper exhibits such diamagnanetism.

Paramagnetic substances have a weak positive magnetic susceptibility and their atoms usually have unpaired electrons of the same spin. Some **metals**, rare earth, and actinides are paramagnetic. All the magnetic moments of the electrons in their atoms do not completely cancel out, and each **atom** has a magnetic moment. Such materials thus have a permanent magnetic moment and they can interact with a magnetic field. An external magnetic field tends to align the magnetic moments in the direction of the applied field, but thermal motion tends to randomize the directions. If only relatively small fractions of the atoms are aligned with the field, then the magnetization obeys Curie's law. Curie's law states that if the applied magnetic field is increased, the magnetization of the material also increases. This is because a stronger magnetic field will align a greater quantity of dipoles. Curie's law also states that the magnetization decreases with increasing **temperature**. The magnetic field produced by the aligned magnetic moments of paramagnetic materials strengthens the external field, but at standard temperatures it averages no more than 10 times stronger than a diamagnetic field and is, therefore, still very weak.

Ferromagnetic materials have the highest magnetic susceptibilities. In these materials, the spins of neighboring atoms do align even in the absence of an externally applied field through a quantum effect known as exchange coupling. Besides **iron**, examples of ferromagnetic materials are nickel, cobalt, and alnico, an aluminum-nickel-cobalt **alloy**. In these materials, all metals, the electrons give rise to permanent dipole moments that can align with those of their neighbors, creating magnetic domains that produce a magnetic field. Above a certain temperature, called the Curie temperature, a ferromagnetic material ceases to be ferromagnetic because the addition of thermal energy increases the motion of the atoms, thus destroying the alignment of the dipole moments. The material then becomes paramagnetic with weak magnetic susceptibility. The magnetic domains of ferromagnetic materials allow them to be turned into permanent magnets. If a ferromagnetic material is placed in a strong magnetic field, its magnetic domains converge into large domains aligned with the externally applied field. Upon removal of the external field, the electrons maintain the alignment and the magnetism remains.

An example of a device incorporating a diamagnet is the metal detector. In this instrument, the magnetic field is generated by an electromagnet, which then forms eddy currents. The magnetic fields from the induced currents are in turn picked up by the metal detector in the form of small currents.

See also Atomic theory; Atoms; Coronal ejections and magnetic storms; Dating methods; Electricity and magnetism; Ferromagnetic; Geographic and magnetic poles; Magnetic field; Paleomagnetics

MANTLE • *see* EARTH, INTERIOR STRUCTURE

MANTLE PLUMES

Convection in Earth's mantle created by the dissipation of internal heat produces up-welling hot columns called mantle plumes and cold, sinking sheets. Numerical modeling suggests the presence of three types of mantle plumes. Regular mantle plumes originate from the core-mantle boundary (a depth of approximately 1,802 mi [2,900 km]) and may be stable for several hundred million years. Such plumes act as fixed reference frames for plate motion. A second type of plume, also originating from the core-mantle boundary, can be bent and move relative to the global circulation in the mantle. Several mantle plumes may also collide to form superplumes. Superplumes rising from the core-mantle boundary may produce additional, secondary plumes that develop above a 416 mi (670 km) boundary layer in Earth's mantle.

Mantle plumes impinge on the base of Earth's **lithosphere** in all plate tectonic settings and result in surface uplift of up to 875 yd (800 m), lithospheric thinning, extensional stress fields, and a thermal anomaly centered on the plume. Heating the base of the lithosphere by mantle plumes may lead to **partial melting** and the formation of **mafic** (i.e., **iron** and magnesium-rich) **magma**. Magma may intrude into fractures formed from extension of Earth's upper, brittle **crust** above mantle plumes to form mafic **dike** swarms. For example, diabase dikes of the Mackenzie dike swarm in north-western Canada that extend for over 1,243 mi (2,000 km) are thought to result from a single mantle plume source. Dikes typically radiate from a point centered above a mantle plume. Radiating arms of dike swarms from different continents have been used to help reconstruct past continent configurations.

Magma may also be extruded as **lava** flows on Earth's surface to form flood basalts over areas 621 mi (1,000 km) or more across. For example, the Paraná and Etendeka volcanics represent pre-breakup volcanism on the South American and African margins of the Tristan Plume and volcanics of the Deccan Traps in western India result from **melting** due to the Reunion Plume. Mantle plumes in the early stages of Earth's history are likely to have been stronger and hotter. Mafic and ultramafic volcanics called komatiites, within Archaean and Paleoproterozoic greenstone belts in **Australia**, Canada, the Baltic Shield and China, have been attributed to mantle plume sources. Some granitoid plutons in Archaean greenstone belts may also be indirectly related to crustal melting by mantle plumes.

Mantle plumes constitute a driving force in the fragmentation and **rifting** apart of continents. For example, the separation of **South America** from **Africa** and Greater India from Australia and **Antarctica** during the break-up of the supercontinent Gondwanaland is interpreted as resulting from rifts linking areas above several mantle plumes. Mantle plume-related rifts are typified by triple junctions where rifts, normal faults and dikes define arms at approximately 120° to each other that intersect above the mantle plume. Frequently, continental breakup and formation of oceanic crust occurs along two of the rift arms, whereas the third arm may be less developed, and constitute a failed rift or aulacogen. For example, a plume-related triple junction occurs over the Afar Plume, above which the Red Sea and Golf of Aden Rifts (along which there is active seafloor spreading) and the eastern, Ethiopian branch of the East African Rift (an intra-continental rift system) intersect. Not all plume-related rifts, however, define triple junctions and four or more rift arms may sometimes be present.

Mantle plumes may play an important role in the formation of mineral deposits e.g., nickel, chromium, platinum, palladium, diamonds, rare earth elements, tin, tantalum, niobium, copper, lead, and zinc. Such deposits may be related to alkaline magmatic fluids associated with mantle plumes, as well as being controlled by extensional structures due to plume-related stresses.

Mantle plumes are not unique to Earth. On Venus, where there is no evidence for **plate tectonics** as is known on Earth, deep rifts called chasmata and prominent radiating fracture systems from central volcanic peaks called novae develop above mantle plumes. Circular to elliptical volcano-tectonic features 37–1,616 mi (60–2,600 km) in diameter called coronae may also be sited above mantle plumes, or result from rifts linking several mantle plumes. Prominent concentric faults rimming smaller coronae are thought to form as a result of collapse due to withdrawal of magma produced by melting above a mantle plume.

See also Convergent plate boundary; Divergent plate boundary; Earth, interior structure; Geothermal deep ocean vents; Hawaiian Island formation; Hotspots; Volcanic eruptions

MAPPING TECHNIQUES

Geological maps portray the distribution of different **rock** types, the location of faults, **shear zones** and **folds**, and the orientation of primary and structural features. Mines, quarries, mineral occurrences, fossil localities, geochronological sampling sites, oil and **water** wells may also be shown. Geological maps illustrate rock relationships that enable the depositional, intrusive, and structural history of an **area** to be established, and the three-dimensional geometry to be visualized. They provide fundamental information for mineral and **petroleum** exploration and for hydrological and environmental investigations.

In small areas such as exploration tenements where detailed maps are required, it is common practice to undertake grid mapping. After a grid is surveyed and pegged, the geologist carries out detailed traverses along grid lines. Rock types, lithological contacts, and alteration are noted and structural measurements made using a compass-clinometer. Information may be recorded by hand on traverse maps or collected digitally. A complete map is compiled by interpolating between gridlines, collecting additional data where necessary. Aerial photographs, **satellite** or other remotely sensed images (as discussed below) serve as the base for recording regional map data. Digital data recorders integrated with **GPS** (global positioning system) location measurements enable lithological and structural data to also be digitally recorded in the field. Data can be directly input into a **GIS** (geographic information system) or custom computer package that enables different attributes to be displayed on a map and spatially analyzed.

A three dimensional, exaggerated view of the landscape is created when pairs of overlapping aerial photographs are viewed through a stereoscope. Stereographic views of aerial photographs assist in the identification and classification of **landforms**, the interpretation of rock types based on characteristic outcrop or **weathering** patterns, and the recognition of tectonic and intrusive structures. Areas where rock formations crop out can also be identified. Where aerial photographs record data in the visible (and sometimes infrared) parts of the **electromagnetic spectrum**, earth-sensing satellites collect data for several different wavelengths or bands. Some bands or ratios of bands highlight vegetation, whereas others respond to differences in water content of soils or different rock types. Individual bands, or ratio of bands are assigned to red, green or blue channels of image processing systems to produce false color images. There has been a marked increase in the resolution of commercially available satellite imagery from 262 ft (80 m) in early Landsat imagery to 2.3 ft (0.70 m) (panchromatic) and 9.2 ft (2.8 m) (multispectral) with the Quickbird-2 satellite. Several other satellites have resolutions of approximately 3.3 ft (1 m) (panchromatic) and between 6.6 and 16.4 ft (2–5 m) (multispectral). Whereas standard satellite imagery uses approximately seven bands, in hyper spectral **remote sensing**, data is collected simultaneously in over 200 narrow, contiguous spectral bands from sensors in high-flying aircraft or satellites. For example, NASA's AVIRIS (Airborne Visible/InfraRed Imaging Spectrometer) maps a strip 6.8 mi (11 km) wide with a ground resolution of approximately 21.8 yd (20 m). Hyperspectral data can be calibrated to distinguish different rock types. Bands that correspond to specific wavelengths at which **minerals** reflect or absorb energy are used to map the distribution of individual minerals, including clays and alteration minerals developed around mineral deposits. Side-looking airborne radar (SLAR) on aircraft or satellites transmits microwave energy and records the energy obliquely reflected from the ground. Radar imagery is useful in mapping areas covered by cloud that obscures normal satellite sensors and in structural mapping, especially in highly vegetated areas. Radar imagery currently has a resolution of 26.2 ft (8 m) or more, although 9.8 ft (3 m) resolution imagery will soon be available.

In contrast to the above techniques that record portions of the electromagnetic spectrum, magnetic and radiometric methods record differences in rock composition. The magnetic signature of a rock is due to the amount of magnetic minerals such as magnetite it contains. Some rock types (e.g., **mafic** volcanics and **banded iron formations**) have a high magnetite content and create magnetic highs. Other rocks low in magnetite (such as quartzite and shale) produce magnetic lows. Faults may be imaged due to magnetite destruction as a result of weathering or alteration during fluid flow along them. Local magnetic highs may indicate addition of magnetic minerals during mineralization and so provide exploration targets. Linear, crosscutting magnetic highs commonly represent mafic dikes. Aeromagnetic data is obtained by flying low altitude, closely spaced parallel paths with an aeroplane or helicopter mounted with (or trailing) a magnetic sensor. Ground magnetic data is recorded using sensors on a tall pole, either handheld or vehicle mounted. Data values are interpolated between recorded measurements. Raw magnetic data is generally first processed to appear as if the inducing **magnetic field** had a 90° inclination (a process called reduction to the pole). This simplifies magnetic anomalies and centers anomalies over the causative rock body. The distribution of different rock types, position of contacts, and form of folds and other structures can be interpreted from contoured or digitally processed magnetic images. Digital enhancements (such as artificial **sun** angles and vertical derivatives) are used to highlight faults, shear zones, and/or lithological contacts. Aeromagnetic data allows geological maps to be made in areas of no outcrop, even below **lakes** or superficial cover.

Airborne gamma ray spectrometry is a technique that measures variations in the potassium, thorium, and uranium content of rocks using sodium iodide crystal detectors mounted in aircraft (radiometric surveys are often carried out at the same time as aeromagnetic surveys). Radiometric data is presented as either individual images portraying the relative amount of each element or images of various element ratios. Radiometric images are useful in mapping compositional variations in granitic and high-grade metamorphic rocks (especially in areas with little or no transported sedimentary cover), rock types such as carbonatite that have unusual amounts or proportions of potassium, thorium and uranium, and alteration zones around mineralized areas. They can also be used to map the distribution of sediments derived by the weathering of granitic and other radiogenic source rocks.

While computer-enhanced images of remotely sensed data are increasingly used in geological interpretation, detailed fieldwork by geologists still provides the backbone for the creation of geological maps.

See also Bathymetric mapping; Cartography; Geologic map; Petroleum, detection; Physical geography; RADAR and SONAR; Remote sensing

MARBLE

Marble is metamorphosed **limestone**, that is, limestone that has been melted and allowed to resolidify. If the original limestone is a calcite limestone, then the marble is a calcite marble (i.e., mostly $CaCO_3$); if the original limestone is a dolomitic limestone, then the marble is a dolomitic or magnesian marble (i.e., mostly $CaMg(CO_3)_2$). In nongeological contexts the term marble is often used to refer to any hard, calcite **rock** that can be cut or polished, including some unmetamorphosed limestones. In **geology**, however, it is reserved strictly for metamorphosed limestones.

Certain marbles have been valued since antiquity for sculpture and for architectural uses. The marbles prized for statuary are usually quite pure (i.e., white in color and free from inclusions or marks) and reflect light softly or semi-translucently due to their property of allowing some incident light to penetrate to a depth of about an inch (1–2.5 cm) before reflecting it.

Some marbles that show colorful patterning are used for decorative architecture. Patterning in marble arises from various trace **minerals**, most often silicates (e.g., **quartz**, **olivine**, garnet), **graphite**, pyrite, and organic substances. The **magma** responsible for metamorphosing the original limestone may also contribute impurities.

Wrinkled thin layers that show in cross-section as sinuous lines are common in marbles. These layers are termed stylolites. Stylolites consist of silicates or other accessory minerals and are usually darker than the surrounding marble. They do not form as sedimentary layers in the original limestone, but result from the selective removal of limestone by **water**. Calcite is a highly soluble mineral; when part of the original limestone is dissolved by infiltrating water, the fine particles that are left are compacted into an irregular layer or stylolite. Comparison of accessory mineral concentrations in adjacent marble and in stylolites shows that 40% or more of a limestone bed may be dissolved in the process of forming stylolites.

Calcite marble, like any other calcite rock, effervesces vigorously (yielding **carbon dioxide** [CO_2]) when tested with hydrochloric acid. Dolomitic marble effervesces more weakly. Otherwise, they are difficult to distinguish.

See also Field methods in geology; Industrial minerals

MARINAS TRENCH • *see* OCEAN TRENCHES

MARINE TRANSGRESSION AND MARINE REGRESSION

Marine transgression occurs when an influx of the sea covers areas of previously exposed land. The reverse process, called marine regression, takes place when areas of submerged seafloor are exposed above sea level by basinward migration of a shoreline. Landward displacement of coastal and marine sedimentary environments accompanies transgression, and a shift from shallow **water** and terrestrial sediments, to deeper-water sedimentary facies, called onlap, indicates a transgression in a vertical succession of sedimentary strata. A shift from deeper marine sediments to terrestrial and fluvial sediments, or offlap, likewise suggests a basinward migration of the shoreline, or a marine regression.

The pattern of onlap and offlap preserved along a continental margin tells its history of alternating transgression and regression. An array of interacting processes determines the position of a shoreline at a specific location, and the geometry of continental margin strata records the combined effects of these interactions. Fluctuation of absolute, global sea level resulting from cyclical growth and decay of Earth’s **polar ice** caps, called eustasy, is only one of the many factors that determine sea level relative to a specific coastal segment. Rates of sediment supply and transport, three-dimensional patterns of deposition and **erosion**, and crustal subsidence and uplift all influence the geometry of onlap and offlap at a particular location. Attempts to define the history of global eustatic sea level change by interpreting the stratigraphic geometry of individual continental margins have been largely unsuccessful, and the difficulty of this scientific problem has underscored the complexity of the systems that regulate shoreline migration.

The study of strata deposited along continental margins under the influence of cyclical Earth processes such as eustatic sea level change is a branch of **stratigraphy** called sequence stratigraphy. Development of this geologic subdiscipline in the early 1970s is largely attributed to **petroleum** industry researchers who first used seismic reflection profiles to map the distribution of oil and gas bearing strata in sedimentary basins. Because relative sea level change determines the location and geometry of these oil-bearing strata along continental margins, sequence stratigraphy is a powerful predictive tool for oil and gas exploration.

See also Beach and shoreline dynamics; Ice ages; Petroleum, detection; Petroleum, history of exploration

MARS • *see* SOLAR SYSTEM

MASS MOVEMENT

Mass movement refers to the downslope movement of **soil**, **regolith**, or **rock** under the influence of **gravity** and without the aid of a transporting medium such as **water**, **ice**, or air. The term is synonymous with **mass wasting** and stands in contrast to mass transport, in which the same kinds of material are transported by water, ice, or air.

Mass movement can occur by a variety of processes including landsliding in all of its forms, **creep**, and solifluction. Rates of mass movement can range from a few millimeters per year in the case of creep or solifluction to tens of meters per second in the case of **catastrophic mass movements** such as debris avalanches. Debris and mud (or earth) flows are generally considered to be forms of mass movement because they are comprised primarily of solid material with only a small proportion of water.

Both mass movement and mass transport are naturally occurring processes that contribute to the cycle of tectonic uplift, **erosion**, transportation, and deposition of sediments. They are responsible for the **topography** of mountain ranges and river canyons that has developed over **geologic time**. Since the Industrial Revolution, however, humans have become increasingly significant agents of mass movement and transport. Catastrophic mass movements at Elm, Frank, and Vaiont were triggered by human activity on or near potentially unstable slopes; the failure of hydraulic structures such as Teton and St. Francis dams have produced major **floods** with great erosional power; and open pit mining involves the movement of cubic kilometers of material over decades of operation. Agriculture is also a large, but subtle contributor to mass movement, because exposed and tilled soil is much more easily eroded than that in its natural state. Recent estimates suggest that humans are currently responsible for the movement of about 37 billion tons of soil and rock per year, and that the cumulative amount of soil and rock moved by humans is the equivalent of a mountain range that is 2.5 miles (4 km) high by 62 miles (100 km) long by 24.8 miles (40 km) wide.

See also Debris flow; Landslide; Mud flow; Rockfall; Slump

MASS WASTING

Mass wasting, or **mass movement**, is the process that moves Earth materials down a slope, under the influence of **gravity**. Mass wasting processes range from violent landslides to imperceptibly slow **creep**. Mass wasting decreases the steepness of slopes, leaving them more stable. While **ice** formation or **water** infiltration in sediments or rocks may aid mass wasting, the driving force is gravity. All mass wasting is a product of one or more of the following mass wasting processes: flow, fall, slide, or **slump**.

The four processes of mass wasting are distinguished based on the nature of the movement that they produce. Flow involves the rapid downslope movement of a chaotic mass of material. Varying amounts of water may be involved. A **mud flow**, for example, contains a large amount of water and involves the movement of very fine-grained Earth materials. Fall involves very rapid downslope movement of Earth materials as they descend (free fall) from a cliff. Ignoring **wind** resistance, falling materials accelerate at 32 ft/sec^2 (9.8 m/sec^2)—the average gravitational force of the earth. Slides result when a mass of material moves downslope, as a fairly coherent mass, along a planar surface. Slumps are similar to slides, but occur along a curved (concave-upward) surface and move somewhat more slowly.

Consider a chunk of **rock** currently attached to a jagged outcrop high on a mountain. It will move to the sea as a result of three processes: **weathering**, mass wasting, and **erosion**.

On warm days, water from **melting** snow trickles into a crack which has begun to form between this chunk and the rest of the mountain. Frigid nights make this water freeze again, and its expansion will widen and extend the crack. This and other mechanical, biological, and chemical processes (such as the growth of roots, and the dissolution of the more soluble components of rock) break apart **bedrock** into transportable fragments. This is called weathering.

Once the crack extends through it and the chunk has been completely separated from the rest of the mountain, it will fall and join the pile of rocks, called talus, beneath it that broke off the mountain previously. This pile of rocks is called a **talus pile**. This movement is an example of mass wasting, known as a **rockfall**. As the rocks in the talus pile slip and slide, adjusting to the weight of the overlying rocks, the base of the talus pile extends outward and eventually all the rocks making up the pile will move down slope a little bit to replace those below that also moved downslope. This type of mass movement is known as rock creep, and a talus pile that is experiencing rock creep is called a rock glacier.

In the valley at the bottom of this mountain, there may be a river or a glacier removing material from the base of the talus slope and transporting it away. Removal and transport by a flowing medium (**rivers**, **glaciers**, wind) is termed erosion.

These processes occur in many other situations. A river erodes by cutting a valley through layers of rock, transporting that material using flowing water. This erosion would result in deep canyons with vertical walls if the erosion by the river were the only factor. Very high, vertical walls, however, leave huge masses of rock unsupported except by the cohesive strength of the material of which they are made. At some point, the stresses produced by gravity will exceed the strength of the rock and an **avalanche** (another type of mass movement) will result. This will move some of the material down the slope into the river where erosion will carry it away.

Erosion and mass wasting work together by transporting material away. Erosion produces and steepens slopes, which are then reduced by mass wasting. The steepness of a natural slope depends on the size and shape of the material making up the slope and environmental factors, principally water content. Most people learn about this early in life, playing in a sandbox or on the beach. If dry **sand** is dumped from a bucket, it forms a conical hill. The more sand dumped, the larger the hill becomes, but the slope of the hill stays the same. Digging into the bottom of the hill causes sand to avalanche down into the hole you are trying to make. Loose, dry sand flows easily, and will quickly re-establish its preferred slope whenever anything is done to steepen it. The flow of sand is a simple example of mass wasting.

If sand is moist, the slope of a sand pile can be higher. A sandcastle can have vertical walls of moist sand when it is built in the morning, but, as the afternoon wears on and the sand dries out, it eventually crumbles and collapses (mass wastes) until a stable slope forms. This is because the water makes the sand more cohesive. With the proper moisture content, there will be both water and air between most of the grains of sand. The boundary between the water and the air has surface tension—the same surface tension that supports water striders or pulls liquids up a capillary tube. In moist sand, surface tension holds the grains together like a weak cement.

However, if sand becomes saturated with water (that is, its pores become completely water-filled as they are in quick sand), then the sand will flow in a process known as lateral spreading. Water-saturated sand flows because the weight of the sand is supported (at least temporarily) by the water, and so the grains are not continuously in contact. The slope of a pile of sand is dependent on water content, and either too little or too much water lowers the stable slope. This illustrates how slope stability is a function of water content.

The steepest slope that a material can have is called the angle of repose. Any loose pile of sediment grains has an angle of repose. As grain size increases, the angle of repose also increases. Talus slopes high on mountain sides may consist of large, angular boulders and can have slopes of up to 45°, whereas fine sand has an angle of repose of 34°. This is the slope that you can see inside a sand-filled hourglass. In nature, however, slopes less than the angle of repose are common because of wind activity and similar environmental processes.

A typical sand dune has a gentle slope on the windward side where erosion by the wind is responsible for the slope. On the leeward side, where sand falls freely, it usually maintains a slope close to the angle of repose. As with loose deposits of particles on land, similar conditions exist if they are under water, although stable slopes are much gentler. When sudden mass wasting events occur under water, large quantities of material may end up being suspended in the water producing turbidity currents that complicate the picture. Such currents occur because a mass of water with sediment suspended in it is denser than the clear water surrounding it, so it sinks, moving down the slope, eroding as it goes. Still, the initial adjustment of the slope was not the result of these currents, so the mechanism that produces turbidity currents is an example of mass wasting.

Most slopes in nature are on materials that are not loose collections of grains. They occur on bedrock or on soils that are bound together by organic or other material. Yet, many of the principles used to explain mass wasting in aggregates still apply. Instead of mass wasting taking place as an avalanche, however, it results from a portion of the slope breaking off and sliding down the hill. These events are usually called landslides, or avalanches—if they are large and damaging—or slumps if they are smaller.

If the gravitational forces acting on a mass of material are greater than its strength, a fracture will develop, separating the mass from the rest of the slope. Usually this fracture will be nearly vertical near the top of the break, curving to a much lower angle near the bottom of the break. Such events can be triggered by an increase in the driving forces (for example, the weight of the slope), a decrease in the strength of the material, or both.

Even solid rocks contain pores, and many of these pores are interconnected. It is through such pores that water and oil move toward wells. Below the **water table**, all the pores are filled with water with no surface tension to eliminate. It might seem that rocks down there would not be affected by rainfall at the surface. As the rains come, however, the water table rises, and the additional water increases the pressure in the fluids in the pores below. This increase in pore pressure pushes adjacent rock surfaces apart, reducing the friction between them, which lowers the strength of the rock and makes it easier for fractures to develop. Elevated pore pressures are implicated in many dramatic mass wasting events.

When mass wasting by flow occurs so slowly that it cannot be observed, it is called creep. Most vegetated slopes in humid climates are subject to **soil** creep, and there are many indicators that it occurs. Poles and fence posts often tip away from a slope a few years after they are placed. Trees growing on a slope usually have trunks with sharp curves at their bases. Older trees are bent more than younger ones. All this occurs because the upper layers of soil and weathered rock move gradually down the slope while deeper layers remain relatively fixed. This tips inanimate objects such as power poles.

It would tip trees, too, except that they grow toward the **Sun**, keeping the trunk growing vertically, and so a bend develops.

This gradual downslope movement requires years to result in significant transport, but because it occurs over a great portion of the surface of the earth it is responsible for most mass wasting.

See also Catastrophic mass movements

MATTHEWS, DRUMMOND (1931-1997)

English marine geophysicist

Drummond "Drum" Matthews had a long, outstanding career in **geology** and geophysics, contributing to the fundamental understanding of the structure and **evolution** of the earth's **crust**.

Matthews grew up near the sea, at Porlock in Somerset, England, and developed a lifelong love of the ocean. He attended Bryanston School in Dorset, before a term in the Royal Navy. He then studied at King's College, Cambridge, specializing in geology and petrology. After graduation, Matthews spent two years (1955–57) in the Falkland Islands, as part of the Dependencies Survey (later the British Antarctic Survey), before returning to Cambridge to complete a Ph.D. in marine geophysics.

In 1962, as part of the International Indian Ocean Expedition, Matthews made a small but detailed survey of a ridge in the north-west Indian Ocean that showed large areas of the seafloor magnetized in opposite polarities. This was to prove a key piece in the puzzle of seafloor creation and the theory of **plate tectonics**. As early as 1915, **Alfred Wegener** (1880–1930) had proposed that there had once been a supercontinent, which he named Pangea, that had slowly moved apart. However, Wegener could not explain how such continental drift occurred, and so his theory was not well received. In the early sixties Harry Hess (1906–1969) hypothesized that seafloor spreading was responsible for the motion of the continents. In 1963, Matthews, with his first graduate student, **Fred J. Vine** (1939-), published a paper, "Magnetic Anomalies Over Ocean Ridges," in *Nature*. In this work, the scientists proposed an idea that, if confirmed, would provide strong support for the seafloor spreading hypothesis. It had long been suspected, but not proven, that the earth's **magnetic field** has undergone a number of reversals in polarity in its long history. Vine and Matthews suggested that if ocean ridges were the sites of seafloor creation, and the earth's magnetic field does reverse, then new **lava** emerging would produce **rock** magnetized in the current magnetic field of the earth. Older rock would have an opposing polarity, depending on when it had been created. By 1966, further studies confirmed the theory for all **mid-ocean ridges**. This provided compelling evidence for sea floor spreading, and an explanation of the mechanism of continental drift.

From 1960 to 1966, Matthews was a Senior Assistant in Research in the Department of Geodesy and Geophysics, and a Research Fellow of King's College, Cambridge. He became an Assistant Director of Research at Cambridge in 1966, and was appointed Head of the Marine Geophysics Group. During his time as Head, the Group contributed to over 70 scientific expeditions and published nearly 200 academic papers, working in areas as diverse as the North Sea, the Eastern Mediterranean, and the Gulf of Oman. In 1971, he was appointed Reader in Marine Geology at Cambridge.

From 1979, Matthews began to study deep crustal seismics that allowed research into the structure and evolution of continental crust. He helped found the British Institutions Reflection Profiling Syndicate (BIRPS), and became its first Director in 1982. BIRPS revealed previously unknown structures in the lower crust and upper mantle. He left BIRPS in 1990, taking early retirement as the result of ill health.

Matthews received many honors and awards recognizing his contributions to geology and geophysics, including the Chapman Medal of the Royal Astronomical Society (1973, with Fred Vine), the Bigsby Medal of the Geological Society of London (1975), the Arthur L. Day prize and lectureship of the National Academy of Sciences (1975, with Vine), the Hughes Medal of the Royal Society (1982, with Vine), the International Balzan Prize (1981, with Vine and Dan McKenzie), and the G. P. Woollard Award of the Geological Society of America (1986). He was a Fellow of the Royal Society from 1974, and was made a Fellow of the American Geophysical Union in 1982. Matthews died at the age of 66 after a long battle with diabetes and a resulting heart condition.

See also Continental drift theory; Earth, interior structure

MAUPERTUIS, PIERRE-LOUIS MOREAU DE (1698-1759)

French astronomer, mathematician, and biologist

A mathematician, biologist, and astronomer, Pierre-Louis Moreau de Maupertuis was a strong proponent of Sir Issac Newton's theory of gravitation, helped confirm Newton's theory on the exact shape of the earth, and formulated the principle of least action in **physics**. Born in Saint Malo, France, Maupertuis had a wide range of scientific interests. As a biologist, he wrote *Systéme de la Nature*, in which he provided the first accurate scientific record of a dominant hereditary trait transmitted among humans. He also introduced the theory of the survival of the fittest in his *Essai de Cosmologie*, a theory that Charles Darwin later expounded to wide acceptance.

Maupertuis may be best known for his formulation in 1744 of the principle of least action, also known as the minimum principle or Maupertuis' principle. Essentially, the principle states that any change that occurs in the universe and nature, such as a moving body or light rays, changes in the most economical path possible. For example, bubbles form in a shape that presents the smallest surface for a given volume of air. In *Essai de Cosmologie*, Maupertuis presented his theory as something that might help prove the existence of God by unifying the laws of the universe. In 1736, Maupertuis led a famous expedition to Lapland near the North Pole that proved Newton's theory that the earth is an oblate sphere (flattened at the poles). The proof was accomplished by measuring the length of degree along a meridian and comparing the findings with the findings of another expedition near the equator in Peru performing similar measurements.

Despite his many accomplishments, Maupertuis was considered arrogant by many of his fellow countrymen. Eventually, Maupertuis became a target of German mathematician Samuel Koenig, who accused him of plagiarism, and of the French author Voltaire (1694–1778), whose satirical writings about Maupertuis were so savage that Maupertuis eventually left France. Maupertuis died in virtual exile in Basel, Switzerland, in the home of Swiss mathematician Johann Bernoulli (1667–1748).

See also Earth (planet); Electromagnetic spectrum

MAXWELL, JAMES CLERK (1831-1879)

Scottish physicist

James Clerk Maxwell was a physicist who introduced a new paradigm with his electromagnetic theory, influencing generations of researchers. Maxwell was without a doubt a child prodigy. At an early age, he solved geometric problems and wrote explanations that intrigued academics. Just as he considered how charged particles interact with their surrounding **area**, one might consider the interaction of the conditions of his inherent nature and the environment of his early childhood. Maxwell's life could make a good case study for the strength of the influences of heredity compared to environment as he had strong influences from both sources.

James Clerk Maxwell was a descendent of the Clerk and the Maxwell families, both with distinguished heritages. His father inherited a house in Edinburgh and land in the countryside. Maxwell was born in 1831 in Edinburgh while his parents were waiting for their country house to be built. They moved shortly after he was born. His father was a lawyer but was not very aggressive in pursuing new business. John Clerk Maxwell enjoyed studying science and building mechanical devices. As young as three years old, James was following his father insisting to know how everything worked. He was very close to his father all of his life. Maxwell's mother died suddenly when he was eight years old. For two years after his mother's death, he was educated by a series of tutors, but none were found suitable for Maxwell and his unique way of learning. His father and his aunt arranged for him to begin studies at the Edinburgh Academy. At the academy, Maxwell started to show his true capabilities and his classmates were less cruel.

In 1847, at age 16, Maxwell began his college studies at the University of Edinburgh. He spent three years there and during this time, he contributed two papers to the Edinburgh Royal Society. When he finished his studies at Edinburgh, his father sent him to Peterhouse, but shortly after beginning there, he transferred to Trinity where he believed he had a better chance for a fellowship. Maxwell studied at Trinity from early 1851 until he graduated in 1854. After graduation, he was awarded the fellowship. Maxwell then applied for a position at Marischal College to be close to his ailing father. However, his father did not live much longer. After his father's death in April 1855, he accepted the position at Marischal.

In 1858, he married the well-educated Katherine Dewar. Two years later, he had to leave Marischal, the victim of an institutional merger. He was immediately invited to teach at King's College, London. It was in London that he did his most prominent work. He remained there until he resigned his post (probably due to exhaustion) in the spring of 1865. He spent most of the next five years at his country home writing a book on his theory. He considered himself retired.

To stay involved in academia, Maxwell did consulting work for Cambridge. His encouraging of Cambridge to offer courses on heat and electromagnetism directly influenced the foundation of the Cavendish Laboratory. It was only natural that the first Cavendish professorship should be offered to him and he accepted. During his eight years as Cavendish professor, he worked to prepare for publication the experiment papers Henry Cavendish had written. It is well accepted that this self-imposed responsibility was influential in bringing due respect to Cavendish's work. In May 1879, as the school year wound down, it was obvious to many that Maxwell's health was beginning to fail. He tried to return to Cambridge in the autumn, but he could scarcely walk. Maxwell died the same year of abdominal cancer at the age of 48.

Maxwell's work leading to his kinetic theory of gases and his theory of electromagnetic fields was a logical advance from James Prescott Joule's work. Both researchers measured the velocity of gas molecules and both recognized that heat was not the fluid that it once was thought to be. The importance of Maxwell's work was the direction that it gave to new understanding. Joule showed only the scientific community what was possible to measure and what might be proven. Maxwell went forward with detailed mathematical models that left no holes unfilled, with one important exception. Maxwell used statistics to show the high probability that proposed laws would direct the behavior of matter. Discussing the probability of natural law took science away from determinism. This opened the door for the modern study of **physics**. Albert Einstein's theory of relativity and the recently nurtured **chaos theory** could not have been developed except for this new philosophical direction.

Maxwell began measuring the average velocity of a gas molecule with the objective to investigate whether the perceived random order of its movement could be predicted with some degree of accuracy. What he found was that the greater the velocity of the molecules, the greater the heat generated. There was a direct relationship between the amount of movement among the molecules and the amount of heat in a gas. In this experimental demonstration, heat was shown undeniably to be a property of particle movement and not a fluid flowing from one object to another. Furthermore, Maxwell's findings showed that the movement of particles could be controlled through increasing or reducing heat.

Maxwell understood Michael Faraday's theory of electric and magnetic fields. He worked to demonstrate what Faraday could not explain himself through complex calculations. Assuming that the **space** surrounding a charged particle contained a field of force, Maxwell created a mathematical model demonstrating all the possible phenomena of electric and magnetic fields. Through this model, Maxwell demonstrated that the electric and magnetic fields worked together. He coined the term "electromagnetic" to name this new breakthrough.

This discovery is important for **chemistry** because it ultimately led to the discovery of the electron. Joseph John Thomson discovered the electron when he was investigating the effects of the electromagnetic field on gases, applying the principles that Maxwell had established. Research on the effects of light on elements was furthered by Maxwell's work. His subsequent work on the velocity of the oscillation of electromagnetic fields demonstrated that light should be considered a form of electromagnetic radiation.

See also Atomic structure; Electromagnetic spectrum; Quantum electrodynamics (QED); Relativity theory

MEANDERS • *see* CHANNEL PATTERNS

MEDIAL MORAINE • *see* MORAINES

MEDITERRANEAN SEA • *see* OCEANS AND SEAS

MELTING • *see* FREEZING AND MELTING

MENDELEEV, DMITRY (1834-1907)

Russian chemist

One of the most unlikely success stories in the history of **chemistry** is that of Dmitry Ivanovich Mendeleev (also Mendeléev, Mendeleef, and Mendeleeff). Mendeleev was born in Tobolsk in western Siberia on February 8, 1834. He was the youngest child in a family of either 14 or 17 children (records do not agree). His father, a teacher at the Tobolsk gymnasium (high school) lost his job after he became blind when Dmitry was still quite young. His mother tried to take over support of the family by building a glassworks in the nearby town of Axemziansk.

Mendeleev was an average student. He learned science from a brother-in-law who had been exiled to Siberia because of revolutionary activities in Moscow. Dmitry completed high school at the age of 16, but only after the family had experienced further misfortune—the death of his father and destruction of his mother's glassworks by fire. In 1850, his mother decided to see that her two youngest children received a college education. She and the children traveled by horse first to Moscow, then on to St. Petersburg. Through the efforts of a family friend, she was able to enroll Dmitry at the Central Pedagogical Institute in St. Petersburg. A few months later, Mendeleev's mother died.

Mendeleev graduated from the Pedagogical Institute in 1855 and then traveled to France and Germany for graduate study. While at Heidelberg with Robert Bunsen, he discovered the phenomenon of critical **temperature**, the highest temperature at which a liquid and its vapor can exist in equilibrium. Credit for this discovery is usually given to Thomas Andrews (1813–1885) who made the same discovery independently two years later.

In 1861, Mendeleev returned to St. Petersburg, where he became professor of chemistry at the Technological Institute. Six years later, he was also appointed professor of general chemistry at the University of St. Petersburg, a post he held until 1890. In that year, he resigned his university appointment in a dispute with the Minister of Education. Three years later he was appointed Director of the Bureau of Weights and Measures, a post he held until his death on February 2, 1907. Mendeleev is remembered as a brilliant scholar, interesting teacher, and prolific writer. Besides his career in chemistry, he was interested in art, education, and economics. He was a man of strong opinions who was not afraid to express them, even when they might offend others. He was apparently bypassed for a few academic appointments and honors because of his irascible nature.

The achievement with which Mendeleev's name will forever be associated was his development of the periodic law. In 1868, he set out to write a textbook in chemistry, *Principles in Chemistry*, that was later to become a classic in the field. Mendeleev wanted to find some organizing principle on which he could base his discussion of Earth's 63 **chemical elements** then known. After attending the Karlsruhe Congress in 1860, he thought that the atomic weights of the elements might provide that organizing principle. He began by making cards for each of the known elements. On each card, he recorded an element's atomic weight, valence, and other chemical and physical properties. Then he tried arranging the cards in various ways to see if any pattern emerged. Mendeleev was apparently unaware of similar efforts to arrange the elements according to their weights made by J. A. R. Newlands (1838–1898) only a few years earlier.

Eventually he was successful. He saw that, when the elements were arranged in ascending order according to their weights, their properties repeated in a predictable, orderly manner. That is, when the cards were laid out in sequence, from left to right, the properties of the tenth element (sodium) were similar to those of the second element (lithium), the properties of the eleventh element (magnesium) were similar to those of the third element (beryllium), and so on.

When Mendeleev arranged all 63 elements according to their weights, he found a few places in which the law appeared to break down. For example, tellurium and iodine were in the wrong positions when arranged according to their weights. Mendeleev solved this problem by inverting the two elements, that is, by placing them where they ought to be according to their properties, even if they were no longer in the correct sequence according to their weights.

Mendeleev hypothesized that the atomic weights for these two elements had been incorrectly determined. He happened to be incorrect in this assumption, and it was not until Henry Moseley discovered atomic numbers in 1914 that the real explanation for inversion was found.

Mendeleev made one other critical hypothesis. He found three places in the **periodic table** where elements appeared to be missing. The blank spaces occurred when Mendeleev insisted on keeping elements with like properties underneath each other in the table, regardless of their weights. He predicted not only that the three missing elements would be found, but also what the properties of those elements would be.

Mendeleev's law was soon vindicated when the three missing elements were found in 1875 (gallium), 1879 (scandium), and 1885 (germanium).

See also Alkaline Earth metals; Atomic mass and weight; Atomic theory; Atoms; Bohr model of the atom; Chemical bonds and physical properties; Chemical elements; Geochemistry

MERCATOR, GERHARD (1512-1594)

Flemish cartographer, geographer, and mathematician

Mercator, the world's most influential mapmaker, modernized **cartography** according to mathematical principles, facilitated navigation by charts, invented the **projection** that bears his name, and coined the term "atlas" to refer to a book of maps.

Born as Gerhardus Cremer, or Kremer, the son of a shoemaker, on March 5, 1512 in Rupelmonde, Flanders, he began using the Latin form of his surname upon entering the University of Louvain in 1530. Both "mercator" in Latin and "cremer" in Flemish, which is cognate with "Kramer" in German, mean "merchant." Raised by his uncle, Gisbert Mercator, who intended him for the Roman Catholic priesthood through the Brethren of the Common Life, he attended secondary school at 'sHertogenbosch and was apparently quite pious. His religious doubts began when his philosophical and theological studies at Louvain prompted him to consider whether biblical and ancient Greek cosmologies could be reconciled. These questions gradually expanded into concern for accurate geography in support of cosmological beliefs. After receiving his M.A. from Louvain in 1532, he studied mathematics, **astronomy**, and geography privately under Reiner Gemma Frisius (1508–1555). Also in the early 1530s he acquired skill as an engraver from Gaspar Van der Heyden (Gaspar à Myrica), a goldsmith in the town of Louvain.

In 1536, Mercator created his first important cartographic work: a globe. His reputation grew internationally over the next few years, especially through his maps of Palestine in 1537, the world in 1538, and Flanders in 1540, as well as his celestial globe of 1537 and his terrestrial globe of 1541. His multifaceted expertise as artist, surveyor, instrument maker, geographer, and mathematician all contributed to his fame. About this time he began experimenting with new projections for maps.

Mercator's frequent travels in search of geographical data aroused suspicion, especially when he, a Catholic, ventured into Protestant lands. In 1544, he was arrested for heresy and jailed for seven months. Although he was released through the intercession of the University of Louvain, the whole experience soured him on the Low Countries and Catholicism. He soon converted to Protestantism and, in 1552, moved to Duisburg, a Protestant enclave in northern Germany, where Duke William of Cleves (1516–1592), brother of the fourth wife of English King Henry VIII, planned to establish a university. The university lasted from 1555 to 1818, but was refounded in 1972. Since 1994, its official name in German has been Gerhard-Mercator-Universität-Gesamthochschule Duisburg.

Mercator served in Duisburg as the duke's cosmographer. He ran his own shop, hired his own artisans, published his own books, and did some teaching. Through the patronage of the court of Cleves, the last four decades of Mercator's life were secure, happy, and productive. Among his best works of this period was his 1554 map of **Europe**.

In 1569, he first published maps based on "Mercator projection." In the systematic vocabulary of cartography, "projection" is a technique or strategy for representing the curved surface of the world or any part of it on the flat surface of a map. There are three general types of projections: cylindrical, conic, and azimuthal, which respectively project the surface of a sphere onto a cylinder, cone, or plane. Some aspect is gained and some aspect is lost with each type. Mercator projection is the best known and most useful of the cylindrical projections. It shows all meridians of longitude as if they were parallel to each other, and thus not converging at the poles; and all parallels of latitude as straight-line segments of equal length, increasing in distance from each other as their distance from the equator increases. The main advantage of Mercator projection is in marine navigation, because all direct sailing courses can be imposed as straight lines. Its main disadvantage is that representations of land areas become more distorted the closer they are to the poles, because of unnatural east-west enlargement.

In 1585, Mercator used the word "atlas" for his book of maps, taking it from the name of the ancient Greek mythological Titan who carried the sky on his shoulders. This gigantic atlas, begun in the 1570s but still unfinished when he died in Duisburg on December 2, 1594, contained corrected versions of the ancient maps of **Ptolemy** (ca. 130) and detailed, up-to-date maps of many parts of Europe.

See also Latitude and longitude; Mapping techniques; Surveying instruments

MERCURY • *see* SOLAR SYSTEM

MERIDIANS • *see* LATITUDE AND LONGITUDE

MESA • *see* LANDFORMS

MESOSPHERE

Based on the vertical **temperature** distribution in Earth's atmosphere, four semi-horizontal layers or "spheres'' can be distinguished: the **troposphere**, **stratosphere**, mesosphere, and thermosphere,. These layers are separated by “pauses,” where no change in the temperature occurs with altitude change: the tropopause (between the troposphere and the stratosphere), the stratopause (between the stratosphere and the mesosphere), and the mesopause (between the mesosphere and the **thermosphere**). The stratosphere and mesosphere together are called the middle atmosphere, and their region also overlaps with the **ionosphere**, which is a region defined on the basis of the electric charges of the particles there.

The mesosphere, which means middle sphere, is the third layer of Earth’s atmosphere, between the stratosphere, and the thermosphere. It is located from about 55 kilometers (35 miles) to 85 kilometers (54 miles) above the surface of Earth. Temperature here decreases with height, so within the mesosphere it is warmest at its lowest level (–5°C, or 23°F), and becomes coldest at its highest level (–80°C, or –112°F). Depending on **latitude** and season, temperatures in the upper mesosphere can be as low as –140°C (–220°F). The temperature in the mesosphere is lower than the temperature of the troposphere or stratosphere, which makes the mesosphere the coldest among the atmospheric layers. It is colder then Antarctica’s lowest recorded temperature, and it is cold enough to freeze **water** vapor into **ice clouds**, which can be seen mostly after sunset.

Although the air in the mesosphere is relatively mixed, it is very thin, resulting in low **atmospheric pressure**. At this height, not only concentrations of **ozone** and water vapor are negligible, air in the mesosphere contains much less **oxygen** than in the troposphere. The mesosphere is also the layer in which many meteors burn up when they enter the earth’s atmosphere, as a result of the collision with some of the gas particles present in this layer.

See also Atmospheric composition and structure; Stratosphere and stratopause; Thermosphere

MESOZOIC ERA

In **geologic time**, the Mesozoic Era, the second era in the **Phanerozoic Eon**, spans the time between roughly 250 million years ago (mya) and 65 mya.

The Mesozoic Era contains three geologic time periods including the **Triassic Period** (250 mya to approximately 206 mya), **Jurassic Period** (206 mya to approximately 144 mya), and the **Cretaceous Period** (144 mya to 65 mya).

The Mesozoic Era begins at the end of the **Permian Period** of the **Paleozoic Era**. The Mesozoic Era’s Cretaceous Period ends with the K-T boundary or **K-T event**.

During the Mesozoic Era the Pangaean supercontinent spanned Earth’s equatorial regions and separated the Panthalassic Ocean and the Tethys Ocean basins. At the start of the Mesozoic Era there was little differentiation or separation between the continental **crust** that would eventually form the North American, European, South American, and African Continents.

Driven by **plate tectonics**, by the middle of the Mesozoic Era (approximately 170 mya) the North American and European continents diverged and the earliest form of the Atlantic Ocean emerged between the continents. At mid-Mesozoic Era, although still united along a broad region, what would become the South American and African Plates became distinguishable in a form similar to the modern continents. **North America** and **South America** remained united by a dry strip of land similar to the isthmus connection that exists today.

Late in the Mesozoic Era, an increase in sea level allowed the confluence of the now distinguishable Pacific Ocean and Atlantic Ocean to provide a wide **water** barrier between North and South America. Much of what are now the eastern and middle portions of the United States was flooded. By the end of the Mesozoic Era, water separated South America from **Africa**. The Australian and Antarctic continents were clearly articulated and the Antarctic continent began a southward migration to the south polar region.

The Mesozoic Era began with a mass extinction and ended with mass extinction. At the end of the Paleozoic Era, almost 80% of marine species became extinct. It would not be until well into the Mesozoic Era that marine life recovered and new reef-building corals evolved. Reptiles dominated the land. Accordingly, the Mesozoic Era is often termed “The Age of Reptiles.”

Mesozoic essentially means “middle animals” and marked a fundamental high point in the number and types of species on Earth. Dinosaurs evolved to rule the Mesozoic Era but non-avian species of dinosaurs became extinct as part of the mass extinction that marked the end of the Mesozoic and start of the **Cenozoic Era**.

The landscape of the Mesozoic Era was also marked by substantial changes in vegetative patterns that altered erosional patterns involved in **landscape evolution**. During the Mesozoic Era, both gymnosperm (conifers, etc.) and subsequently angiosperm plants evolved in forms comparable to their modern form. Plant growth also allowed the subsequent development of extensive **coal** beds.

Like the Paleozoic, the Mesozoic Era closed with an episode of extinction. More than 70% of all existing life forms became extinct by the Mesozoic Era–Cenozoic Era boundary (also known as the Cretaceous-Tertiary boundary), including virtually all of the dinosaurs.

During the Mesozoic Era large meteor impacts were frequent. The impact at the start of the Mesozoic Era has been estimated to be of such force as to be able to creating a 350 km **impact crater**, The K-T event crater (i.e., the Chicxulub crater) measures 170 km in diameter.

See also Archean; Cambrian Period; Cenozoic Era; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Holocene Epoch; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Eon; Quaternary Period; Silurian Period; Supercontinents; Tertiary Period

METALS

Metals are rarely encountered in their elemental state in nature. They must first be extracted from the ground as an ore, which is then treated to release the metal. Some metals may be extracted from their natural state by electrolysis (for example sodium), while others may need more drastic treatment (such as **iron** or zinc). **Precious metals** (e.g., gold, silver, platinum) are relatively rare and as a result have a high value in the marketplace.

There are approximately 90 elements that can be described as metals (the number can fluctuate slightly depending upon the precise definition of a metal used to categorize the elements). Regardless, they all have various characteristics in common ranging from bonding to chemical nature.

In general, metals are elements that conduct **electricity**, are malleable, and are ductile. Another group of elements—the metalloid or semi-metal elements—share some properties with the metals and some with the nonmetals. There are eight of these elements and they are semiconductors.

Metals are usually solids at standard **temperature** and pressure (STP). One exception to this is mercury, which is a liquid at STP. As is to be expected from the fact that most metals are solids at STP, the majority of metals also have **melting** and boiling points that are high.

Electrical current is not the only thing that metals conduct. They are also efficient conductors of heat.

Metals have a shape that can be easily changed by hammering (i.e., they are malleable). Metals are also ductile (i.e., they can be drawn out into a long wire). With the exception of gold and copper, metals are silvery gray in color and all metals take a polish well.

Chemically, the atoms of a metallic element are bonded to their neighbors by metallic bonds, producing a giant metallic lattice structure. Metallic elements have relatively few electrons in their outermost shells. When metallic bonds are formed, these outermost electrons are lost into a pool of free or mobile electrons. Thus, the metallic lattice structure is actually comprised of positive ions packed closely together and a pool of freely moving electrons surrounding them. These free electrons are referred to as delocalized because they are not restricted to orbiting one particular ion or **atom**. This pool of delocalized electrons allows a metal to conduct an electrical charge because the electrons are free to move. Alloys also have this type of bonding, allowing them to conduct electricity as well. For this same reason metals are also good conductors of heat.

The close packing of the metal ions (the ions are packed as close as they can possibly be) explains the high density of the majority of the metals. A metal with a high molecular mass will have a greater density than one with a lower molecular mass even though their atomic radii may be similar. **Lead** and **aluminum** have similar atomic sizes, but lead has a much larger molecular mass and consequently it has a much higher density.

The malleability of metals is due to the regular arrangement of ions within the metallic lattice. The bonds holding the lattice in place are strong, but they are somewhat flexible. Layers of ions can slip over each other without the structure of the molecule being destroyed. This also explains why metals are ductile. Both of these characteristics are more noticeable when the metal is hot. The metallic lattice is also responsible for the appearance of some metals. When a metal is examined under a microscope, it is seen to have a crystalline structure that is made of regions called grains. The smaller the grain size the more closely packed are the ions of the metal and the stronger and harder it is. If hot metal is allowed to cool slowly, the resulting grains are large, making a metal that is easy to shape. This process is known as annealing. When a hot metal is cooled quickly, the **crystals** produced are small. When this cooling is carried out in **water**, it is called quenching. Quenching will produce a metal that is strong, hard, and brittle.

Many materials are referred to as metals when in fact they are not. The true metals are actually elements, whereas the false metals are alloys—composites of elements. For example, the element iron is a metal. Steel, however, is not a true metal, since it is an **alloy** containing a mixture of iron and carbon—the relative ratios of the two materials control the physical characteristics of the product. Alloys have different properties than the materials from which they are produced, so by careful blending the exact properties required can be manufactured.

Metals have a wide range of uses. For example, copper is used to conduct electricity in cables (an excellent conductor and very ductile). Tin is used to coat cans for food storage (non-poisonous and **corrosion** resistant). Aluminum is used as kitchen foil (high malleability). Iron is used as a fencing material (easily workable and relatively resistant to corrosion). Alloys made from metals have different uses. Steel—an alloy of iron and carbon—is used widely in the construction industry because of it great strength and ease with which it can be initially formed to create specific shaped structural components (e.g., beams, girders, etc.) Solder—tin and lead—is used for joining metals together because of its low melting point. Brass—copper and zinc—is fashioned into ornaments, buttons, and screws because of its high strength, low weight, and corrosion resistance.

See also Atomic theory; Atoms; Electricity and magnetism; Minerals

METAMORPHIC ROCK

Metamorphic **rock** is rock that has changed from one type of rock into another. The word metamorphic (from Greek) means "of changing form." Metamorphic rock is produced from either igneous rock (rock formed from the cooling and hardening of **magma**) or sedimentary rock (rock formed from compressed and solidified layers of organic or inorganic matter). Most of Earth's **crust** is made up of metamorphic rock. Igneous and **sedimentary rocks** become metamorphic rock as a result of intense heat from magma and pressure from tectonic shifting. Although the rock becomes extremely hot and under a great deal of pressure it does not melt. If the rock melted, the process would result in igneous, not metamorphic rock. Metamorphic alteration of rock causes the texture and/or mineral composition to change. New textures are formed from a process called recrystallization. New **minerals** (which are simply various combinations of elements) are created when elements recombine.

There are two basic types of metamorphic rock: regional and thermal. Regional metamorphic rock, found mainly in mountainous regions, is formed mainly by pressure, as opposed to heat. Different amounts of pressure produce different types of rock. The greater the pressure, the more drastic the change. Also, the deeper the rock the higher the **temperature**, which adds to the potential for diverse changes. For example, a pile of mud can turn into shale (a fine-grained sedimentary rock) with relatively low pressure, about 3 mi (5 km) down into the earth. With more pressure and some heat, shale can transform into **slate** and mica. Metamorphic rock found closer to Earth's surface, or produced by low pressure, characteristically splits or flakes into layers of varying thickness. This is called foliation. Slate is often used as roofing tiles and paving stones. With lots of pressure and increasing heat, rock called **schist** forms. Schist, which is a medium-grained regional metamorphic rock also has a tendency to split in layers, is subjected to high temperatures, and often contains **crystals**, such as garnets. **Gneiss** (pronounced "nice") is formed by a higher pressure and temperature than schist. These rocks are coarse grained and, although layered as schist is, do not split easily. Essentially, metamorphic rocks are made of the same minerals as the original rock or parent rock but the various minerals have been rearranged to make a new rock.

Thermal metamorphic rock, also called contact metamorphic rock, is formed not only by considerable pressure but, more importantly, by intense heat. Imagine molten rock pushing up into Earth's crust. The incredible pressure fills any empty space, every nook and cranny, with molten rock. This intense heat causes the surrounding rock to completely recrystallize. During recrystallization, the chemical composition regroups to form a new rock. An example of this type of thermal metamorphic rock is **marble**, which is actually **limestone** whose calcite has recrystallized. **Sandstone** made mostly of **quartz** fragments recrystallizes into quartzite. Thermal metamorphic rocks are not as common or plentiful as regional metamorphic rocks. Sometimes a metamorphic rock can become metamorphosed. This is known as polymetamorphism.

See also Metamorphism

METAMORPHISM

Metamorphism refers to the physical and chemical changes that rocks undergo when exposed to conditions of high **temperature**, high pressure, or some combination thereof. Rocks that have undergone metamorphism exhibit chemical and structural changes that result from the partial or complete recrystallization of **minerals** within them. These transformations occur while the **rock** is in the solid state, i.e., no **melting** occurs during metamorphism. The conditions of high temperature and pressure under which metamorphism occurs are typically the result of processes such as mountain building, plate convergence, volcanism, and **sedimentation**.

Any type of rock may be metamorphosed and several agents can be involved in altering a parent rock into its metamorphic product. The composition of the parent rock limits the mineral composition of the product, although subsurface gases and fluids may contribute new elements. Thermal energy at depth, either from the **geothermal gradient** or from plutonic activity, may provide the energy for recrystallization of the rock. As the temperature increases, volatile components such as **water** and **carbon dioxide** can be released causing chemical changes to the minerals within the parent rock. In addition, the temperature increase may cause the rock to behave plastically in response to stresses acting on it, frequently resulting in a contorted appearance. Pressure on the parent rock may be a result of the overlying rock, known as lithostatic or confining pressure, or may be due to forces acting in a particular direction due to tectonic activity, known as directed pressure. Pressures within the rock may cause the instability of certain minerals in favor of those that are more stable under the new conditions. The pressure may also be localized on irregularities on the boundaries of individual grains. Recrystallization of a rock undergoing directed pressure typically results in the development of a foliated rock fabric, in which the axes of the minerals are aligned with the differential pressures based on the stability of the crystal lattice to those pressures. The development of such **crystals** during metamorphism may be heavily influenced by amount of time that the rock is exposed to the conditions. The mobilization of ions that supports crystal growth within the rock can require extensive periods of time to produce larger mineral grains.

Metamorphism may occur in a number of forms, each having different results and areal extent. Contact metamorphism is the baking of **country rock** immediately adjacent to an intruded **magma** body. This type of metamorphism, also known as thermal metamorphism, is caused by the high temperatures associated with an igneous intrusion. The rock is altered only in a zone, called an aureole, which can range from a few centimeters to several hundred meters in width. These zones may occur very near the surface and pressure plays an insignificant role in the process. In the case of cataclastic or dynamic metamorphism, rocks in a localized zone undergo mechanical disruption without significant mineralogical change. This is a near-surface phenomenon that is often associated with faulting and occurs at low temperature. Regional metamorphism, as the name suggests, encompasses large areas and is associated with large mountain building and plutonic events. Relatively high temperature and intense, directed pressures are common in this process. The differential stress associated with regional, or dynamothermal, metamorphism frequently yields foliated rock.

See also Metamorphic rock; Shock metamorphism

METEOROIDS AND METEORITES

The word meteor is derived from the Greek *meteron*, meaning something high up. Today, however, the term is used to describe the light phenomena produced by the entry of a meteoroid into Earth's atmosphere. A meteoroid is defined to be any solid object moving in interplanetary **space** that is much larger than an **atom** or a molecule, but smaller than a few meters in diameter. A visual meteor, or shooting star, is produced whenever a meteoroid is vaporized in Earth's upper atmosphere. If a meteoroid survives its passage through the atmosphere without being fully vaporized and falls to the ground, it is a called a meteorite.

Upon entering Earth's upper atmosphere, a meteoroid begins to collide with an ever-increasing number of air molecules. These collisions will both slow the meteoroid down and heat its surface layers. At the same time the meteoroid is being decelerated, that energy is transferred from the meteoroid to the surrounding air. Some of the meteoroid's lost energy is transformed into light; it is this light that we observe as a meteor. As the meteoroid continues its journey through the atmosphere, its surface layers become so hot that vaporization begins. Continued heating causes more and more surface mass to be lost in a process known as ablation, and ultimately the meteoroid is completely vaporized.

The amount of surface heating that a meteoroid experiences is proportional to its surface **area**, and consequently very small meteoroids are not fully vaporized in the atmosphere. The size limit below which vaporization is no longer important is about 0.0004 in (0.01 mm). The smallest of meteoroids can safely pass through Earth's atmosphere without much physical alteration, and they may be collected as micrometeorites at Earth's surface. It is estimated that 22,000 tons (20,000 metric tons) of micrometeoritic material fall to Earth every year.

Visual meteors (shooting stars) are produced through the vaporization of millimeter-sized meteoroids. The speed with which meteoroids enter Earth's atmosphere varies from a minimum of 7 mi/sec (11 km/sec) to a maximum of 45 mi/sec (72 km/sec). The meteoroid ablation process typically begins at heights ranging 62–71 mi (100–115 km) above the earth's surface, and the whole meteoroid is usually vaporized by the time it has descended to a height of 43.5 mi (70 km).

Astronomers have found that the visually observed meteors are derived from two meteoroid populations: a continuously active, but sporadic, background and a number of specific sources called meteoroid streams.

On any clear night of the year, an observer can expect to see 10–12 sporadic meteors per hour. Sporadic meteors can appear from any part of the sky, and about 500,000 sporadic meteoroids enter Earth's atmosphere every day.

Meteor activity is often described in terms of the number of meteors observed per hour. The observed hourly rate of meteors will be dependent upon the prevalent visual conditions. Factors such as the presence of a full **moon**, local light pollution, and **clouds** will reduce the meteor count and, hence, lower the observed hourly rate. Astronomers often quote a corrected hourly rate which describes the number of meteors that an observer would see, each hour, if the observing conditions were perfect.

Observations have shown that the corrected hourly rate of sporadic meteors varies in a periodic fashion during the course of a day. On a typical clear night, the hourly rate of sporadic meteors is at a minimum of about six meteors per hour at 6 P.M.. The hourly rate climbs steadily during the night until it reaches a maximum of about 16 meteors per hour around 4 A.M.

This daily variation in the hourly rate of sporadic meteors is due to Earth's **rotation** in its orbit about the **Sun**. In the evening, a sporadic meteoroid has to catch up with Earth if it is to enter the atmosphere and be seen. This is because at about 6 P.M. local time an observer will be on that part of Earth's surface which is trailing in the direction of Earth's motion. In the early morning, however, the observer will be on the leading portion of Earth's surface, and consequently Earth will tend to "sweep up" all the meteoroids in its path. An observer will typically see two to three times more sporadic meteors per hour in the early morning than in the early evening; and will see them at higher speeds relative to Earth.

Meteor showers occur when Earth passes through the tube-like structure of meteoroids left in the wake of a comet. Such meteoroid tubes—or as they are more commonly called, meteoroid streams—are formed after a comet has made many repeated passages by the Sun. Meteoroid streams are composed of silicate (i.e., rocky) grains that were once embedded in the surface ices of a parent comet. Grains are released from a comet's nucleus whenever solar heating causes the surface ices to sublimate. New grains are injected into the meteoroid stream each time the comet passes close by the Sun.

The individual dust grains (technically meteoroids once they have left the comet) move along orbits that are similar to that of the parent comet. Gradually, over the course of several hundreds of years, the meteoroids form a diffuse shell of material around the whole orbit of the parent comet. Provided that the stream meteoroids are distributed in a reasonably uniform manner, a meteor shower will be seen each year when the earth passes through the stream. The shower occurs at the same time each year because the position at which the meteoroid stream intersects Earth's orbit does not vary much from one year to the next. There are long-term variations, however, and the days during which a shower is active will eventually change.

When Earth passes through a meteoroid stream, the meteoroids are moving through space along nearly parallel paths. Upon entering Earth's atmosphere, however, a perspective effect causes the shower meteors to apparently originate from a small region of the sky; this region is called the radiant.

The radiant is typically just a few degrees across when projected onto the night sky. A meteor shower is usually, but not always, named after the constellation in which the radiant falls on the night of the shower maximum. The Orionid meteor shower, for example, is so named because on the night of the shower maximum (October 21st) the stream radiant is located in the constellation of Orion. Some meteor showers are named after bright stars. The Eta Aquarid meteor shower, for example, is so named because on the night of the shower maximum (May 3rd) the radiant is close to the seventh brightest star in the constellation of Aquarius (by convention the brightest stars in a constellation are labeled after the Greek alphabet, and accordingly, the seventh letter in the Greek alphabet is eta).

Probably the best-known meteor shower is the one known as the Perseid shower. This shower reaches its peak on the night of August 12th each year, but meteors can be observed from the stream for several weeks on either side of the maximum. The shower's radiant first appears in the constellation of Andromedia in mid-July, and by late August it has moved into the constellation of Camelopardalis. The radiant is in the constellation of Perseus on the night of the shower maximum.

The steady eastward drift of the radiant across the night sky is due to the motion of Earth through the Perseid meteoroid stream. The nearly constant year-to-year activity associated with the Perseid meteor shower indicates that the stream is very old. Essentially, the earth encounters about the same number of Perseid meteoroids each year even though it is sampling different segments of the stream. Since 1988, however, higher than normal meteor rates have been observed about 12 hours before the time of the traditional shower maximum (August 12th). This short-lived period (approximately half an hour) of high activity is caused by new meteoroids that were ejected from the stream's parent comet, Comet Swift-Tuttle, in 1862. Comet Swift-Tuttle last rounded the Sun in late 1992, and it is expected that higher than normal meteor rates will be visible half-a-day before the time of the "traditional" Perseid maximum until around 2015.

Another meteor shower known as the Leonid occurs every year in November, caused by the tail of comet Tempel-Tuttle, which passes through the inner **solar system** every 32–33 years. Such a year was 1998; on November 17 and 18, 1998, observers on Earth saw as many as 200 meteors an hour. The shower was so intense that it generated widespread concern about the disruption of global telecommunications and the possible damage or destruction of space telescopes. Partly as a result of careful preparation by **satellite** and **telescope** engineers, however, concerns appeared to be minimal.

If a meteoroid is to survive its passage through Earth's atmosphere to become a meteorite, it must be both large and dense. If these physical conditions are not met, it is more than likely that the meteoroid, as it ploughs through Earth's atmosphere, will either crumble into many small fragments, or it will be completely vaporized before it hits Earth's surface. Most of the meteoroids that produce meteorites are believed to be asteroidal in origin. In essence, they are the small fragmentary chips thrown off when two minor planets (**asteroids**) collide. Meteorites are very valuable then, for bringing samples of asteroidal material to Earth. A few very rare meteorite samples are believed to have come from the planet Mars and the Moon. It is believed that these rare meteorite specimens characterize material that was ejected from the surfaces of Mars and the Moon during the formation of large impact craters.

Accurate orbits are presently known for just four recovered meteorites (the Pibram meteorite, which fell in the Czech Republic in 1959; the Lost City meteorite, which fell in Oklahoma in 1970; the Innisfree meteorite, which fell in Alberta, Canada, in 1977; and the Peekskill meteorite, which fell in New York State in 1992). All four of these meteorites have orbits that extend to the main asteroid belt between the planets Mars and Jupiter.

Meteorites are superficially described as being either falls or finds. A meteorite fall is scientifically more useful than a find because the exact time that it hit Earth's surface is known. Finds, on the other hand, are simply that—meteorites that have been found by chance. The largest meteorite find to date is that of the 66 ton (60 metric ton) Hoba meteorite in South **Africa**. Meteorites are either named after the specific geographic location in which they fall, or after the postal station nearest to the site of the fall.

An analysis of meteorite fall statistics suggests that about 30,000 meteorites of mass greater than 3.5 oz (100 g) fall to Earth each year. Of these meteorites, the majority weigh just a few hundred grams, only a few (about 5,000) weigh more than 2.2 lb (1 kg), and fewer still (about 700) weigh more than 22 lb (10 kg). In general, the number of meteoroids hitting the earth's atmosphere increases with decreasing meteoroid mass: milligram meteoroids, for example, are about a million times more common than meteoroids weighing a kilogram.

Meteorites are classified according to the amount of silicate and metallic nickel-iron that they contain. Three main meteorite types are recognized; these are the irons, the stones, and the stony-irons. The **iron** meteorites consist almost entirely of nickel-iron, while the stone meteorites are mostly silicates. The stony-iron meteorites contain both nickel-iron and silicates. The stony meteorites are further divided into chondrites and achondrites. The term chondrite is applied if the meteorite is composed of many small, rounded fragments (called chondrules) bound together in a silicate matrix. If no chondrules are present then the meteorite is an achondrite. Most (about 85%) of the stony meteorites are chondrites. Meteorite fall statistics indicates that about 96% of meteorites are stony, 3% are irons and 1% are stony-irons.

Even though many thousands of meteorites fall to Earth each year it is rare for one to hit a human being. The chances of a human fatality resulting from the fall of a meteorite have been calculated as one death, somewhere in the world, every 52 years. Thankfully, no human deaths from falling meteorites have been reported this century. A woman in Sylacauga, Alabama, was injured, however, by a 8.6 lb (3.9 kg) meteorite that crashed through the roof of her house in 1954. Another close call occurred in August of 1991, when a small meteorite plunged to the ground just a few meters away from two boys in Noblesville, Indiana.

In contrast to the situation with human beings, meteorite damage to buildings is much more common—the larger an object is the more likely it will be hit by a meteorite. A farm building, for example, was struck by a meteorite fragment in St. Robert, Quebec in June of 1994. Likewise, in August 1992, a small village in Uganda was showered by at least 50 meteorite fragments. Two of the meteorites smashed through the roof of the local railway station, one meteorite pierced the roof of a cotton factory, and another fragment hit an oil storage facility. One of the more spectacular incidents of meteorite-sustained damage in recent times is that of the Peekskill meteorite which fell in October of 1992 and hit a parked car.

See also Astronomy; Barringer meteor crater; Impact crater; Murchison meteorite; Space and planetary geology

METEOROLOGY

Meteorology is a science that studies the processes and phenomena of the atmosphere. Accordingly, a person who studies the atmosphere is called a meteorologist. Meteorology consists of many areas: physical meteorology, dealing with physical aspects of the atmosphere such as rain or cloud formation, or rainbows and mirages; synoptic meteorology, the analysis and forecast of large-scale **weather** systems; dynamic meteorology, which is based on the laws of theoretical **physics**; climatology, the study of the climate of an **area**; aviation meteorology, researching weather information for aviation; **atmospheric chemistry**, examining the chemical composition and processes in the atmosphere; atmospheric optics, analyzing the optical phenomena of the atmosphere such as halos or rainbows; or agricultural meteorology, studying the relationship between weather and vegetation. While meteorology usually refers to the study of the earth's atmosphere, atmospheric science includes the study of the atmospheres of all the planets in the **solar system**.

Greek philosopher and scientist Aristotle (384–322 B.C.) is considered the father of meteorology, because he was the first one to use the word meteorology in his book *Meteorologica* around 340 B.C., summarizing the knowledge of that time about atmospheric phenomena. He speculatively wrote about clouds, rain, snow, **wind**, and climatic changes, and although many of his findings later proved to be incorrect, many of them were insightful. The title of the book refers to all the things being in the sky or falling from there, which at that time was called a meteor.

Although systematic weather data recording began about the fourteenth century, the lack of weather measuring instruments made only some visual observations possible at that time. The real scientific study of atmospheric phenomena started later with the invention of devices to measure weather data: the thermometer in about 1600 for measuring **temperature**, the barometer for measuring **atmospheric pressure** in 1643, the anemometer for measuring wind speed in 1667, and the hair hygrometer for measuring **humidity** in 1780. In 1802, the first cloud classification system was formulated, and in 1805, a wind scale was first introduced. These measuring instruments and new ideas made possible gathering of actual data from the atmosphere giving the basis for scientific theories for properties of the atmosphere (pressure, temperature, humidity, etc.) and its governing physical laws.

In the early 1840s, the first **weather forecasting** services started with the invention of the telegraph transporting meteorological information. At that time, meteorology was still in the descriptive phase, still on an empirical basis with little scientific theories and calculations involved, although weather maps could be drawn, and storm systems and surface wind patterns were being recognized.

Meteorology became more scientific only around World War One, when Norwegian physicist Vilhelm Bjerknes (1862–1951) introduced a modern meteorological theory stating that weather patterns in the temperate middle latitudes are the results of the interaction between warm and cold air masses. His description of atmospheric phenomena and forecasting techniques were based on the laws of physics, exploring the science of dynamic meteorology, assuming that knowing about the atmospheric conditions now, and knowing the governing physical laws for its movements, predictions for the future are possible.

By the 1940s, upper-level measurements of pressure, temperature, wind, and humidity clarified more about the vertical properties of the atmosphere. In 1946, the process of **cloud seeding** was invented which made possible some weather modification experiments. In the 1950s, radar became important for detecting **precipitation** of a remote area. Also in the 1950s, with the invention of the computer, weather forecasting became not only quicker but also more reliable, because the computers could solve the mathematical equations of the atmospheric models much faster than manually before. In 1960, the first meteorological **satellite** was launched to provide 24-hour monitoring of weather events worldwide.

These satellites now give three-dimensional data to high-speed computers for faster and more precise weather predictions. These days the computers are capable of plotting the observation data, and solving huge models not only for short-time weather forecasting, but also climatic models on time scales of centuries, for climate change studies. Meteorology has come a long way since Aristotle. Even so, the computers still have their capacity limits, the models are still with many uncertainties, and the effects of the atmosphere on our complex society and environment can be serious. Many complicated issues remain at the forefront of meteorology—including air pollution, **global warming**, El Niño events, climate change, the **ozone** hole, acid rain—making meteorology today a scientific area still riddled with many challenges and unanswered questions.

See also Air masses and fronts; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pollution; Clouds and cloud types; El Niño and La Niña phenomena; Greenhouse gases and greenhouse effect; Isobars; Scientific data management in Earth Sciences; Weather balloon; Weather forecasting methods; Weather radar; Weather satellite; Weathering and weathering series; Wind chill; Wind shear

MID-ATLANTIC RIDGE • *see* MID-OCEAN RIDGES AND RIFTS

MID-OCEAN RIDGES AND RIFTS

The ocean floor is mountainous and uneven, much like Earth's surface. As oceanographers began mapping the ocean bottom, they discovered that the sea floor is full of vast rising slopes, or ridges, and dramatic open valleys, or rifts. During World War II, oceanographer William Maurice Ewing began mapping the complex ocean bottom with sophisticated instruments such as sonar depth finders and underwater cameras that helped trace the contours of the ocean bottom. Ewing set out to measure and record a massive chain of undersea mountains called the Midatlantic Ridge. When Ewing and his crew began mapping the massive ridge, they encountered a problem: the sonar beams were bouncing back. This problem led to another great discovery. They realized that there were frequent oceanic earthquakes occurring along the ridge. This was an exciting discovery because it opened up the possibility that oceanic earthquakes might be connected to ridges and rifts. Using data from other expeditions, Bruce Charles Heezen (b. 1924) more accurately measured the Midatlantic Ridge as he began mapping the ocean floor. The Ridge measured up to 1.9 miles (3 km) high and 45,954 miles (73,940 km) long. Interestingly, however, he detected a gully in the ridge that led to the Heezen-Ewing theory in 1958, which formally recognized the Midatlantic Ridge as containing a rift. Their discovery sparked interest in other scientists and explorers who questioned the existence of other rifts in ocean ridges.

In the late 1950s, American and Soviet oceanographic vessels began mapping the ocean floor so that their nuclear submarines could navigate deep underwater. The ensuing data provided maps that revealed extraordinary natural phenomena. Submerged peaks and undersea ridges form a continuous mountain chain that reaches up to 10,000 feet (3,048 m) and measures 40,000 miles (64,360 km). This mid-ocean ridge system circles the earth several times and is now known as one of Earth's dominant features, extending over an **area** greater than all the major land mountain ranges combined. Along a great deal of its length, the ridge system is sliced down its middle by a sharp gully, a rift that is the outlet of powerful heat flows. **Temperature** surveys demonstrate that heat seeps out of the earth in these mountainous regions of the middle Atlantic, adding to the complexity of the ocean floor. This evidence of heat emitting from Earth's giant cracks and faults helped reveal the existence of earthquakes and **volcanic eruptions** beneath the ocean. Most of this heat and movement take place in the Atlantic Ocean where the ridge is steeper and more jagged than in the Pacific or Indian **Oceans**.

In some of the most active volcanic areas another unusual natural phenomenon takes place, discovered by **Harry Hammond Hess**. Hess studied the isolated mountains rising from the ocean floor and discovered "sea-mounts," which he named **guyots** in honor of the Swiss-American geographer Arnold Henry Guyot (1807–1884). Hundreds of these strange undersea protrusions lie under the Pacific Ocean, all of which were probably sunken islands created from volcanic **lava**. Some of these guyots broke away and gradually wandered further away from the volcanoes. Before oceanographers studied the floor of the great oceans, there was little evidence to support the **continental drift theory**, which assumed that all the great landmasses were once joined in one supercontinent. Hess's discovery of guyots and other studies of seafloor movement helped reveal the spreading movement of the ocean floor. Hess proposed that hot **rock** swelled from deep within the earth, constantly forcing the ridges and rifts to part and spread. Later these discoveries of seabed movement helped build on the findings of Alfred L. Wegener's thoery of continental drift.

See also Sea-floor spreading

MID-PLATE EARTHQUAKES

Mid- or intra-plate earthquakes are those that occur within the boundaries of the major crustal plates. Most (over 90%) earthquakes occur along the tectonically active plate boundaries, where the major crustal plates are moving past and/or away from each other. However, large and damaging earthquakes can and have occurred within the plates, far from the boundaries. For example, the New Madrid earthquakes of 1811–1812 occurred well within the North American Plate. Both intra-plate and plate boundary earthquakes occur along faults, zones of crustal weakness that have experienced and/or continue to experience relative movement and deformation associated with tectonic activity. Intra-plate earthquakes are difficult to explain because they occur in the relatively stable interiors of plates. Seismic data, however, indicate that **faults and fractures** are very common in the upper **crust** of the earth. These act as zones of weakness that can be reactivated if the *in situ* stress field becomes favorable. Studies of the New Madrid events indicate that the earthquakes occurred along fault zones of an ancient rift system within the North American Plate.

In the winter of 1811–1812, one of the largest sequences of earthquakes in recorded history occurred within the North American Plate near the town of New Madrid, Missouri. The magnitudes of at least three of those earthquakes are estimated to have been greater than 8.0 on the **Richter scale**. The earthquakes were felt over an **area** of millions of square miles and as far away as Boston. During the quakes, large areas of land rose and large areas of land fell several feet. **Lakes** were created and islands disappeared. The Mississippi River was disrupted, waterfalls formed, and large waves swamped many boats. During one of the events, the Mississippi River gave the illusion of flowing backwards. In 1895, another significant but smaller **earthquake** occurred in this region near the town of Charleston, Missouri. That quake was felt in 23 states.

Earthquakes along plate boundaries are relatively understandable given the tectonic activity localized there. Intra-plate earthquakes are much more enigmatic. One explanation offered for the New Madrid earthquakes are the increased stresses that were induced in the region by the unloading of the **ice** sheets that covered much of the northern United States until about 20,000 years ago. Geological evidence indicates that large earthquakes have occurred in this region before 1811. Some modeling suggests that the stresses that caused the earthquakes may persist for thousands of years in the future.

See also Plate tectonics; Rifting and rift valleys

MIGMATITE

A migmatite, or "mixed rock" in Greek, is a banded, heterogeneous **rock** composed of intermingled metamorphic and igneous components. Veins, contorted layers, and irregular pods of silica-rich **granite** occur within the structure of foliated **iron** and magnesium-rich metamorphic rocks like **gneiss**,

schist and amphibolite. Because metamorphic rocks form by recrystallizaton of **minerals** without **melting**, and **igneous rocks** like granite form by crystallization of minerals from molten **magma**, it is difficult to explain their coexistence in a single rock. It is clear, however, that migmatites form at the threshold between high-grade metamorphic recrystallization, and complete igneous melting. Migmatites were partially melted during formation.

Some migmatites appear to have formed by intrusion of liquid granitic melt into a preexisting banded **metamorphic rock**. In these examples, the granite inclusions have sharp contacts with the metamorphic bands, and cut across the metamorphic fabric in places. In other cases, the boundaries between metamorphic and igneous components are gradational, or indistinct, suggesting that at least some migmatites form during a single phase of **partial melting** and fractional recrystallization. Metamorphic and igneous petrologists have rigorously debated these two hypotheses regarding the formation of migmatites. As is sometimes the case, both hypotheses are probably correct, and some migmatites form in several phases of **metamorphism** and melting, while others from during a single phase.

Migmatites generally occur in plate tectonic settings where regional belts of continental **crust** have been subjected to very high temperatures and pressures. The metamorphic portion of most migmatites includes the minerals horneblende, **plagioclase feldspar**, and garnet. This mineral assemblage indicates so-called amphibolite-grade metamorphism typical of convergent plate tectonic boundaries where rocks are subjected to very high pressures, strong directional stresses, and high temperatures.

See also Plate tectonics

MILANKOVITCH CYCLES

The Serbian astronomer Milutin Milankovitch (1879–1958) developed a theory that explained climatic variations in astrophysical terms. He was particularly concerned with the origin of an **ice** age during the Pleistocene. Through observations of the stars, Milankovitch found that the basic elements that govern the earth's orbit around the **Sun** are not constant. First, he noticed that the eccentricity of the elliptical path of the earth's **revolution** around the Sun changes with cycles of roughly 100,000 and 400,000 years. Second, he found that the obliquity, that is the angle of the earth's spin axis with the plane of its eccentric orbit changes with a frequency of roughly 41,000 years between 22 and 25 degrees. Third, he took into consideration that the earth's axis of revolution behaves like the spin axis of a top that is winding down. The spin axis traces a circle on the celestial sphere over a period of approximately 22,000 years. This motion, which is called the precession of the equinoxes, was probably detected by Hipparch of Nikaia (about 150 B.C.). It is the reason why a person then Aries-born, is born under the sign of Pisces today.

In 1920, Milankovitch calculated the effect of each of these cycles on the total summer insulation at a **latitude** of 65 degrees North. He reasoned that at this latitude, small insulation changes might have a big effect because a decrease of the summer insulation allowed the snow and ice of winter to persist through the summer months, and into the following winter. In this way, big ice sheets can develop and accelerate in a positive feed-back through enhancing the northern latitude albedo.

It required a few decades for the theory to have its break-through. Today, however, it is generally accepted that Milankovitch's theory describes the main causes for the waxing and waning of the Pleistocene ice sheets correctly. Proof for this theory is derived from cyclic variations of the chemical and paleontological composition of marine, lacustrine, and terrestrial sediments. Investigations into the temporal variation of the ratio of **oxygen** isotopes in particular have shown that Milankovitch cycles do indeed influence the **climate** greatly on time scales covering thousands to hundreds of thousands of years, although continental distribution, ocean patterns, the total solar irradiance, and other factors play an additional role. The Sun, for instance, is obviously a prominent factor for climatic variations on a time scale between years to a few thousand years, which is summarized in the so-called Athenian hypothesis.

See also Ice ages

MILLER-UREY EXPERIMENT

A classic experiment in molecular biology and genetics, the Miller-Urey experiment, established that the conditions that existed in Earth's primitive atmosphere were sufficient to produce amino acids, the subunits of proteins comprising and required by living organisms. In essence, the Miller-Urey experiment fundamentally established that Earth's primitive atmosphere was capable of producing the building blocks of life from inorganic materials.

In 1953, University of Chicago researchers Stanley L. Miller and Harold C. Urey set up an experimental investigation into the molecular origins of life. Their innovative experimental design consisted of the introduction of the molecules thought to exist in early Earth's primitive atmosphere into a closed chamber. Methane (CH_4), hydrogen (H_2), and ammonia (NH_3) gases were introduced into a moist environment above a water-containing flask. To simulate primitive **lightning** discharges, Miller supplied the system with electrical current.

After a few days, Miller observed that the flask contained organic compounds and that some of these compounds were the amino acids that serve as the essential building blocks of protein. Using chromatological analysis, Miller continued his experimental observations and confirmed the ready formation of amino acids, hydroxy acids, and other organic compounds.

Although the discovery of amino acid formation was of tremendous significance in establishing that the raw materials of proteins were easy to obtain in a primitive Earth environment, there remained a larger question as to the nature of the origin of genetic materials—in particular the origin of DNA and RNA molecules.

Stanley Miller working in the lab where he simulated atmospheric conditions similar to those on Earth 3.5 billion years ago and created organic compounds. © *Bettmann/Corbis. Reproduced by permission.*

Continuing on the seminal work of Miller and Urey, in the early 1960s Juan Oro discovered that the nucleotide base adenine could also be synthesized under primitive Earth conditions. Oro used a mixture of ammonia and hydrogen cyanide (HCN) in a closed aqueous enviroment.

Oro's findings of adenine, one of the four nitrogenous bases that combine with a phosphate and a sugar (deoxyribose for DNA and ribose for RNA) to form the nucleotides represented by the genetic code: adenine (A), thymine (T), guanine (G), and cytosine (C). In RNA molecules, the nitrogenous base uracil (U) substitutes for thymine. Adenine is also a fundamental component of adenosine triphosphate (ATP), a molecule important in many genetic and cellular functions.

Subsequent research provided evidence of the formation of the other essential nitrogenous bases needed to construct DNA and RNA.

The Miller-Urey experiment remains the subject of scientific debate. Scientists continue to explore the nature and composition of Earth's primitive atmosphere and thus, continue to debate the relative closeness of the conditions of the Miller-Urey experiment (e.g., whether or not Miller's application of electrical current supplied relatively more electrical energy than did lightning in the primitive atmosphere. Subsequent experiments using alternative stimuli (e.g., ultraviolet light) also confirm the formation of amino acids from the gases present in the Miller-Urey experiment. During the 1970s and 1980s, astrobiologists and astrophyicists, including American physicist **Carl Sagan**, asserted that ultraviolet light bombarding the primitive atmosphere was far more energetic that even continual lightning discharges. Amino acid formation is greatly enhanced by the presence of an absorber of ultraviolet radiation such as the hydrogen sulfide molecules (H_2S) also thought to exist in the early Earth atmosphere.

Although the establishment of the availability of the fundamental units of DNA, RNA and proteins was a critical component to the investigation of the origin of biological molecules and life on Earth, the simple presence of these molecules is a long step from functioning cells. Scientists and evolutionary biologists propose a number of methods by which these molecules could concentrate into a crude cell surrounded by a primitive membrane.

See also Cosmology; Evolution, evidence of; Evolutionary mechanisms; Solar system

MINERALOGY

Mineralogy is the study of **minerals**. Rocks in the earth's **crust** are composed of one or more minerals. A mineral in the geologic sense is a naturally occurring, inorganic, crystalline solid. A particular mineral has a specific chemical composition. Each mineral has its own physical properties such as color, hardness, and density.

Most minerals are chemical compounds that are made of two or more different elements. The composition of a mineral is shown by its chemical formula, which states each of the **chemical elements** present in the mineral as well as the ratios of each element. For example, the mineral **quartz** has the chemical formula SiO_2. This means that quartz is made of the elements **silicon** (Si) and **oxygen** (O). The formula also shows that for every one silicon **atom**, two oxygen atoms are present. The mineral orthoclase has the chemical formula $KAlSi_3O_8$. A molecule of orthoclase contains one potassium (K) atom, one **aluminum** (Al) atom, three silicon atoms, and eight oxygen atoms. Some minerals always have the same chemical formula. Quartz always is composed of SiO_2 and halite is always made of sodium (Na) and chlorine (Cl), with the chemical formula NaCl. Some minerals can have more than one chemical formula, depending on their composition. Sometimes an element can substitute for another in a mineral. This occurs when the atoms of two elements are the same charge and close to the same size. For example, an **iron** (Fe) atom and a magnesium (Mg) atom are both about the same size, so they can substitute for each other. The chemical formula for the mineral **olivine** is $(Mg,Fe)_2SiO_4$. The (Mg,Fe) indicates that either magnesium, iron, or a combination of the two may be present in an olivine sample.

Native elements are minerals that are composed of only one element. These are the substances that dietitians call minerals. Examples of native elements include gold (Au), silver (Ag), and platinum (Pt). Two other native elements are **graphite** and **diamond**, both of which are entirely made of **carbon** (C).

All minerals are crystalline solids. A crystalline solid is a solid consisting of atoms arranged in an orderly three-dimensional matrix. This matrix is called a crystal lattice. A crystalline solid is composed of molecules with a large amount of order. The molecules in a crystalline solid occupy a specific place in the arrangement of the solid and do not move. The molecules not only occupy a certain place in the solid, but they are also oriented in a specific manner. The molecules in a crystalline solid vibrate a bit, but they maintain this highly ordered arrangement. The molecules in a crystalline solid can be thought of as balls connected with springs. The balls can vibrate due to the contractions and expansions of the springs between them, but overall they stay in the same place with the same orientation. It is not easy to deform a crystalline solid because of the strong attractive forces at work within the structure. Crystalline solids tend to be hard, highly ordered, and very stable.

Under ideal conditions, mineral crystals will grow and form perfect crystals. An ideal condition would be in a place where the crystals are allowed to grow slowly without disturbances, such as in a cavity. A perfect crystal has crystal faces (planar surfaces), sharp corners, and straight edges. The external crystal form is controlled by the internal structure. When the atoms in a crystal are arranged in a perfectly orderly fashion, the crystal will also be formed in a perfect orderly fashion. Even if a perfect crystal is not formed, the internal crystalline structure can be shown. Many minerals exhibit a property called cleavage. A mineral that has cleavage will break or split along planes. If the internal structure is formed in an orderly crystal arrangement, then the breaks will occur along the planes of the internal crystal structure.

There have been over 3,500 minerals identified and described. Only about two dozen of these are actually common. There are a limited number of minerals, mainly because there are only a certain number of chemical elements that can combine to form chemical compounds. Some combinations of elements are unstable, such as a potassium-sodium or a silicon-iron compound. In addition, only eight elements are found abundantly in the earth's crust, where minerals are formed. Oxygen and silicon alone account for more than 74% of the earth's crust. These factors place a limit on the number of possible minerals.

The minerals that have been discovered and studied can be placed into one of five groups. These groups are the silicate minerals, carbonate minerals, oxides, sulfides, and halides. The silicate minerals are those that contain silica, a combination of silicon and oxygen. Examples of silicates include quartz, orthoclase, and olivine. The silicate minerals are the most common, making up approximately one-third of all known minerals. They are composed of building blocks called the silica tetrahedron. A silica tetrahedron is one silicon atom and four oxygen atoms. The atoms are arranged in a four-faced pyramidal structure (the tetrahedron) with the silicon atom in the center. The silicon atom has a +4 charge, and each of the four oxygen atoms have a –2 charge. As a result, a silicon tetrahedron has a net charge of –4. Because of this charge, it does not occur in isolation in nature. A silica tetrahedron is always bound to other atoms or molecules.

There are two types of silicate minerals, the ferromagnesian and the nonferromagnesian silicates. Ferromagnesian silicates are those containing iron, magnesium, or both. These minerals tend to be dark colored and more dense than the nonferromagnesian silicates. An example of a ferromagnesian silicate is olivine. Nonferromagnesian silicates do not have iron and magnesium. These minerals are light colored and less dense. The most common nonferromagnesian silicates are the feldspars.

The carbonate minerals contain the carbonate ion, $(CO_3)^{2-}$. Calcite ($CaCO_3$), the main component of **limestone**, is an example of a carbonate mineral. The oxides are minerals that contain an element combined with oxygen. An example of an oxide is hematite, Fe_2O_3. The sulfides contain a cation combined with sulfur (S^{2-}). An example of a sulfide is galena (PbS), which is **lead** (Pb) combined with sulfur. The halides all contain halogen elements, such as chlorine and fluorine (F). Examples of halite minerals include halite (NaCl) and fluorite (CaF_2).

All minerals posses specific physical properties such as color, luster, crystal form, cleavage, fracture, hardness, and specific **gravity**. The physical characteristics of a mineral depend on its internal structure and chemical composition. The physical properties of minerals can be used for identification purposes by mineralogists. Color is the least reliable of the physical properties. Many minerals display a variety of colors due to impurities. Some generalizations can be made, however. Ferromagnesian silicates, for example, are usually black, brown, or dark green. The luster of a mineral refers to the way in which light is reflected off the mineral. Two types of luster can be displayed: metallic or nonmetallic.

The crystal form of a mineral is also a physical property specific for the type of mineral being observed. This property is most easily observed when the mineral has formed a perfect crystal. Cleavage is the tendency of a mineral to break or split along planes. There are different types of cleavage that correspond to the different internal crystal structures that make up individual minerals. Fracture occurs when a mineral does not break along smooth planes, rather along irregular surfaces. Some minerals display cleavage, others display fracture.

The hardness of a mineral is its resistance to being scratched. The Mohs hardness scale can be used to determine how hard a mineral is by determining what will scratch its surface. The specific gravity of a mineral is the ratio of its density to the density of **water**. For example, a mineral with a specific gravity of 4.0 is four times as dense as water, meaning that an certain volume of the mineral would weigh four times as much as an equal volume of water. The specific gravity of a mineral is determined by its composition and structure.

Mineralogy is an interesting science that studies the nature of minerals—naturally occurring, inorganic crystalline solids. There are many different minerals, each with its own properties determined by its chemical composition. Mineralogists continue to search for new, useful minerals in the earth's crust.

See also Chemical bonds and physical properties; Crystals and crystallography; Ferromagnetic; Mohs' scale

MINERALS

The term mineral is often used to denote any material that occurs naturally in the ground, including oil and **natural gas**. However, mineralogists and geologists restrict its use to naturally occurring solids having specific chemical compositions. For example, all solid forms of pure silica (SiO_2) are minerals, including natural **glass** and **quartz**, but **coal** is not a mineral because it has no definite and universal chemical composition.

Solids produced by living things—bones, shells, pearls, and the like—are a special case. Scientists usually consider these objects non-minerals even when they have definite a chemical composition, as do the calcium carbonate ($CaCO_3$) shells of marine animals. The distinction is more professional than physical; mineralogists study minerals, but biologists study shells and bones, so shells and bones must not be minerals. However, biological solids that have been completely rearranged at the atomic level are officially regarded as minerals. For example, **graphite** and **diamond** formed by metamorphosis of coal are minerals.

Because solidity is part of the definition of a mineral, substances may change from mineral to non-mineral or vice versa by **melting** or solidifying. Liquid **water** has a definite chemical composition (H_2O) but is not considered a mineral because it is not solid; **ice**, however, is a mineral. **Magma** or molten **lava** are not minerals because they have no definite, universal composition and are liquids; solidified, they become mixtures of specific minerals.

The atoms making up a mineral may be arranged either randomly, like mixed marbles in a bag, or in an orderly pattern, like squares on a chessboard. If a mineral's atoms show long-range organization, the mineral is termed crystalline. The objects commonly called crystals are crystalline minerals of relatively large size that happen to have developed smooth faces. Many crystals, however, are too small to see with the naked eye, and most have imperfectly developed faces or none at all. Most rocks consist of chunks of several crystalline minerals fused together. In some rocks, such as **granite**, these individual pieces are large enough to see, while in others, such as **slate**, they are too small.

If a mineral's atoms are randomly arranged it is termed an **amorphous** mineral or a mineraloid. The most common amorphous mineral is glass—the solid formed by cooling magma or molten lava so quickly that its atoms do not have time to organize into crystals. Molten lava quenched in air or water, or intrusive magma cooled rapidly by contact with **rock** form glasses. All glasses are metastable; that is, they tend to lapse into crystalline form, much as water molecules in cold vapor organize themselves into snowflakes. In the case of glasses, this spontaneous crystallization process is termed devitrification. The processes of devitrification causes glasses to be rare in proportion to their age. Most natural glasses date from the last 60 or 70 million years, a mere tenth of the time since the beginning of the **Cambrian Period**. The remainder have devitrified.

Because **oxygen**, **silicon**, and other elements may be present in any ratio in a glass, depending on the composition of the original melt, some mineralogists do not consider glasses minerals and restrict the term mineral to naturally occurring crystals. For the remainder of this article, the term mineral will be used in this restricted sense.

Earth's **crust** and mantle consist almost entirely of minerals, yet the number of known minerals is less than 3,000. Two factors limit the number of possible and actual minerals. First, a crystal's atoms must be arranged in some periodically repeating, three-dimensional pattern, but only a finite number of such patterns exists. Second, there are only a few score naturally occurring elements, many of which are rare and eight of which—oxygen, silicon, **aluminum**, **iron**, calcium, sodium, potassium, and magnesium, in order of decreasing common-

Display of minerals in Seitenstetten, Austria. *© Massimo Listri/Corbis. Reproduced by permission.*

ness—comprise 98.5% of Earth's crust by weight. Oxygen alone makes up approximately 47% of the crust by weight (over 90% by volume), and silicon makes up approximately another 27%. The number of minerals that can form is therefore finite, and many of those that could theoretically form do so rarely.

The atoms of the two most common elements on earth, silicon and oxygen, readily arrange themselves into tetrahedra (four-sided pyramids) having a silicon **atom** at the center and an oxygen atom at each point. This unit is the silicate radical, $(SiO_4)^{4-}$. Silicate radicals can link into sheets, chains, or three-dimensional frameworks by sharing oxygen atoms. If every oxygen atom participates in two tetrahedra, then the overall ratio of silicon to oxygen is 1:2, and the resulting chemical formula is that of silica, SiO_2. Minerals built mostly of silica are termed silicate minerals. The mineral quartz is pure crystalline silica; other silicate minerals result when atoms of elements other than silicon are introduced at regular intervals. For example, some of the tetrahedra in the silicate framework may be centered on aluminum atoms rather than silicon atoms. In this case, atoms of other elements (usually calcium, potassium, or barium) must be present to balance the ionic charges in the framework. The silicate minerals having this particular structure are the feldspars, which make up approximately 60% of the earth's crust by volume.

When atoms of elements other than silicon unite with oxygen to form the basic building block of a mineral, nonsilicate minerals result: carbonates from **carbon** (e.g., calcite [$CaCO_3$]), sulfates from sulfur (e.g., anhydrite [$CaSO_4$]), phosphates from phosphorus (e.g., apatite [$Ca_5(PO_4)_3F$]), and the oxide minerals, in which O^{2-} alternates with positively charged ions (e.g., spinel [$MgAl_2O_4$]). Other mineral groups do not involve oxygen at all, including the halides (e.g., salt [NaCl]), the sulfides (e.g., pyrite [FeS_2]), and the native elements (pure sulfur, carbon, gold, etc.).

Although for simplicity's sake chemical formulas have been identified with mineral species in the preceding paragraph, the identity and properties of a mineral depend not only on what kinds of atoms compose it but on the arrangement of these atoms in **space**. Diamond and graphite, for instance, both consist entirely of carbon atoms and so have the same chemical formula (C), but differ in structure. A mineral's structure, in turn, depends partly on its chemical formula and partly on its history, that is, on the changes in pressure, **temperature**, and chemical context through which it has passed in reaching its present state. A simple example of a mineral structure recording process is the production of glass by rapid cooling of molten silica. To hold a piece of glass is to know a small, specific piece of history; this silica must have cooled rapidly. The dependence of mineral formation on time and temperature is exactly analogous to cookery. Indeed, geologists routinely speak of how the formation of minerals in large bodies of cooling magma is influenced by the "baking" of the magma. Minerals are therefore studied not only for their directly useful properties but for what their very existence reveals about the history of the earth.

See also Crystals and crystallography; Minerology; Obsidian

MIOCENE EPOCH

Notable in the development of primates and human **evolution**, are fossilized remains of *Ardipithecus ramidus*, perhaps one of the earliest identifiable ancestors of man. Fossilized remains found in Ethiopia date to approximately six million years ago, near the end of the Miocene Epoch. Importantly, the fossilized bones found provide evidence that *Ardipithecus ramidus* could walk upright. Anthropologists assert that the ancestral line between apes and humans diverged six to eight million years ago from a common ancestor that lived during the Miocene Epoch.

In **geologic time**, the Miocene Epoch occurs during the **Tertiary Period** (65 million years ago to 2.6 million years ago—and is also sometimes divided or referred to in terms of a Paleogene Period from 65 million years ago to 23 million years ago) and a Neogene Period (23 million years ago to 2.6 million years ago) instead of a singular Tertiary Period—of the **Cenozoic Era** of the **Phanerozoic Eon**. The Miocene Epoch is the fourth epoch in the Tertiary Period (in the alternative, the earliest epoch in the Neogene Period).

The Miocene Epoch ranges from approximately 23 million years ago (mya) to 5 mya. The Miocene Epoch was preceded by the **Oligocene Epoch** and was followed by the **Pliocene Epoch**.

The Miocene Epoch is further subdivided into (from earliest to most recent) Aquitanian (23 mya to 21 mya), Burdigalian (21 mya to 16 mya), Langhian (16 mya to 14 mya), Serravallian (14 mya to 10 mya), Tortonian (10 mya to 7 mya), and Messinian (7 mya to 5 mya) stages.

Craters dating to the end of the Oligocene Epoch and start of the Miocene Epoch can be studied in Northwest Canada and in Logancha, Russia. Smaller impact craters dating to the end of the middle of the Miocene Epoch are evident in Russia and Germany.

Other notable finds in the **fossil record** that date to the Miocene Epoch include evidence of the continued extensive development of grasslands initiated during the preceding Eocene and Oligocene Epochs. The grassland development offered a chance for grazing animals to become well established. Many of the modern migratory patterns date to the Miocene Epoch. The fusion of the Arabian plate to the Eurasian plate provided a land bridge from **Africa** to **Asia** allowing migration of species and mixing of genetic traits among reproductively compatible sub-species.

The paleobotanical record provides evidence that kelp **forests** also became well developed during the Miocene Epoch as the climate cyclically warmed and cooled, but more generally became less humid.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Evolution; Evolution, evidence of; Evolutionary mechanisms; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Pleistocene Epoch; Precambrian; Proterozoic Eon; Quaternary Period; Silurian Period; Triassic Period

MISSISSIPPIAN PERIOD

Shallow, low-latitude **seas** and lush, terrestrial swamps covered the interior of the North American continent during the Mississippian Period of the **Paleozoic Era**, from about 360 to 320 million years ago. The Pennsylvanian and Mississippian Periods are uniquely American terms for the upper and lower sections of the Carboniferous, a geologic period defined by a sequence of **coal** and limestone-bearing strata delineated by European geologists in the early nineteenth century. In 1822, English geologists William Conybeare (1787–1857) and William Phillips (1775–1828) coined the term Carboniferous for the period of **geologic time** typified by the British Coal Measures, Millstone Grit, and Mountain **Limestone**, all important strata that appeared on Adam Smith's (1769–1839) famous map of the **geology** of England in 1815. (They also included the Old Red **Sandstone** that was later reassigned to the Devonian Period.)

Coal-bearing strata analogous to the British Coal Measures also exist in **North America**, especially in Pennsylvania. In 1870, Alexander Winchell (1824–1891), used the term Mississippian to describe a series of limestone beds exposed below the coal beds in the Mississippi River valley near St. Louis. After much confusion regarding mapping and **correlation** of American Carboniferous strata, United States Geological Survey (USGS) geologist Henry Shaler Williams (1847–1918), suggested the terms Pennsylvanian and Mississippian in 1891. While these sub-divisions of the Carboniferous are commonly used in North American, European geologists never adopted them. Furthermore, the Mississippian-Pennsylvanian boundary is younger than the Lower Carboniferous–Upper Carboniferous boundary, so the terms cannot be interchanged.

During the Mississippian, the North American and Eurasian continents were part of a northern supercontinent called Laurasia. The similarity between Carboniferous rocks of **Europe** and North America is thus not coincidental, as the two regions were connected at the time. **South America**, **Africa**, India, **Australia** and **Antarctica** were assembled into the southern supercontinent of Gondwana. Polar **glaciation** was minimal, and Laurasia was located near the equator. Tropical rainforests and swamps rich with vegetation that would later become coal beds grew on exposed land, and shallow, tropical seas covered large regions of the present-day American Midwest and South. Mississippian marbles and limestones, filled with **fossils** of flower-like invertebrates called crinoids, intricate corals, and other Paleozoic carbonate organisms, are exposed throughout the American Midwest.

See also Fossil record

MISTRAL • *see* SEASONAL WINDS

MOHOROVICIC, ANDRIJA (1857-1936)

Croatian seismologist and meteorologist

Croatian seismologist and meteorologist, Andrija Mohorovicic was the first one to suggest the existence of a boundary surface separating the **crust** of the earth from the underlying mantle. This layer, which is 5 mi (8 km) deep under the **oceans** and about 20 mi (32 km) deep under the continents in average, was later named the **Mohorovicic discontinuity**. In 1970, a large crater on the far side of the **Moon** was also named in Mohorovicic's honor.

Mohorovicic was born on in Volosko, now in Croatia. After spending his early school years in Volosko, then Rijeka, he studied **physics** and mathematics at the Faculty of Philosophy, in Prague. In 1882, he started his nine-year carrier in the Nautical School in Bakar teaching **meteorology**, and beginning his scientific work. A few years later, in 1887, he founded a meteorological station in Bakar.

In 1891, Mohorovicic transferred to Zagreb, and in 1892, he became the head of the Meteorological Observatory in Zagreb. Here he studied and wrote mainly about **clouds**, rainstorms, thunderstorms, tornadoes, whirlwinds, hail, and winds, focusing interest on these meteorological phenomena and their scientific interpretation, as well as studying the **climate** of Zagreb. In 1892, he started astronomical observations of stars. In 1893, he established a network of stations for thunderstorm observations. Still in 1893, he received his doctor of philosophy degree at the Zagreb University. In 1899, he founded hail stations, and the same year he started a research project about harnessing **wind** energy.

In 1901, Mohorovicic became director of the meteorological service of Croatia and Slovenia. In his meteorological research, he was still interested in the detection of tornadoes and thunderstorm tracking. Mohorovicic's last contribution to meteorology was in 1901, when he published his paper on vertically decreasing atmospheric **temperature**. After the turn of the twentieth century, Mohorovicic's scientific interest focused exclusively on the problems of **seismology**.

Mohorovicic gradually extended the activities of the observatory to other fields of geophysics: seismology, geomagnetism and gravitation, although as chief of the observatory, Mohorovicic was still responsible for recording all the meteorological data for Croatia and Slovenia. The **earthquake** in 1909 in Croatia directed his interest towards the examination of seismic waves, and in 1910, Mohorovicic published his findings. His plot (arrival time versus epicenter distance to recording station) used the data from 29 stations within 1,491 mi (2,400 km) of the epicenter. He concluded that at around 31 mi (50 km), there must be an abrupt change in the material in the interior of the earth, because he observed an abrupt change in the velocity of the earthquake waves. Although this conclusion was not accepted immediately, a few years later, in 1915, other researchers confirmed it. This discontinuity region under all the continents and oceans is today called the Mohorovicic discontinuity, or in short, the Moho. Although others later refined the study of crust and upper mantle with the application of new methods, Andrija Mohorovicic was clearly a pioneer of this **area**.

Mohorovicic also published a paper in 1909 on the effect of earthquakes on buildings that described periods of oscillation, which was considered by his contemporaries to be ahead of the times not only in his own country, but worldwide. In 1910, he became an associate university professor. From 1893 to 1917, he taught subjects in the fields of geophysics and **astronomy** at the Faculty of Philosophy in Zagreb. In 1893, Mohorovicic first became a corresponding member, then in 1898, a full member of the Academy of Sciences and Arts in Zagreb. Although at the end of 1921 he retired, he worked actively until the late 1920s. He died in 1936, and he is buried in Zagreb.

Because of his extensive work studying epicenters, seismographs, and travel-time curves, much of our knowledge of how earthquakes occur, as well as the current models of the earth's structure can be traced back to the work of Andrija Mohorovicic. Among his other achievements, Mohorovicic also found a procedure for identifying the unique location of earthquake epicenters and formulated an analytical expression for the increase of elastic wave velocity with depth, which was later named Mohorovicic's law. Mohorovicic's thoughts and ideas were original, and he focused his interest in more than one area: the effects of earthquakes on buildings, harnessing the energy of the bora, models of the earth, locating earthquake epicenters, seismographs, and many other subjects also in meteorology. Andrija Mohorovicic was an outstanding scientist and researcher, and his scientific work in the field of seismology rightfully gave him world recognition, making him one of the founders of modern seismology.

See also Earth, interior structure

MOHOROVICIC DISCONTINUITY (MOHO)

The Mohorovicic discontinuity, sometimes referred to as "Moho," is the boundary where Earth's **crust** meets Earth's upper mantle (approximately 31 mi/50 km below the surface), and where seismic waves travel at a different and more rapid rate than the crust or mantle. The Moho is named after **Andrija Mohorovicic** (1857–1936), a Croatian meteorologist and seismologist who was fascinated with the faults and movements in the earth's infrastructure that result in earthquakes. The discovery of the Moho was most important because it helped scientists discover a second layer, or mantle, inside the earth. It also helped scientists to determine more accurately where this second layer was located in relation to Earth's surface, or crust.

Since the early 1900s, scientists were almost certain that Earth, like an onion, was made up of many layers, but they did not know exactly where the layers started and ended. In 1906, Mohorovicic studied Yugoslavian **earthquake** records, which revealed the existence of two different sets of earth shock waves from one earthquake. Because the second set of waves exactly mirrored the first set, Mohorovicic discovered that the additional set was actually the first bouncing back from a resistant surface, or a layer of different material inside the earth. This resistant surface, or discontinuity, allowed Mohorovicic to postulate the existence of a second stratum of material under the crust. He did this by gauging the time between the waves, which helped him determine how far this layer resided from the earth's surface.

Mohorovicic also noticed from these experiments that the waves, or tremors, traveled at different speeds depending on the thickness of the material inside Earth. This information helped scientists discover the different types of rocks in areas where drilling was impossible. For example, the lowest level of the crust is composed of basaltic **rock**, the material that rests next to the mantle. After the Moho was discovered, scientists were able to further plot seismic wave movements on sensitive shock recording devices called seismographs. From this information, we know that the outer crust of Earth is 20–25 mi (32–40 km) thick except under many places in the ocean, where it is only 3 mi (4.8 km) thick. The mantle is only the second interior layer. Deeper within the earth lies the most interior layer, Earth's core. We know from mountains and valleys that Earth's surface has changed and shifted with the ages. Similar to Earth's uneven crust, Earth's mantle is thought to be comparably uneven, mostly caused by enormous pressures inside Earth forcing the weaker areas of the rocky sub-layers out of alignment. When the weaker sub-layers, or plates, give way to pressure or stronger plates, earthquakes result. Ever since the existence of the mantle became certain, scientists sought to probe into the physical nature of the earth's inner layer. And because the Moho is located so much closer to the surface beneath the ocean, there were plans in the late 1950s to drill into the Moho from floating platforms out at sea. After a number of test drillings, and a drop in funding, the project—Project Mohole—was abandoned in the mid-1960s.

See also Crust; Earth (planet); Earth, interior structure

MOHS' SCALE

Mohs' hardness scale provides an index and relative measure of mineral hardness (i.e., resistance to abrasion). German geologist Frierich Mohs (1773–1839) devised a scale with specimen **minerals** that offered comparison of "hardness" qualities that allows the assignment of a Mohs hardness number to a mineral. Mohs' scale utilizes 10 specific representative materials that are arranged numerically from the softest (1) to the hardest (10). The reference minerals are (1) talc, (2) **gypsum**, (3) calcite, (4) fluorite, (5) apatite, (6) orthoclase **feldspar**, (7) **quartz**, (8) topaz, (9) corundum, and (10) **diamond**.

The softest mineral, talc, can be used in body powder. The hardest, diamond, is used in drill bits to cut through the most dense crustal materials. Mohs' scale is a relative index scale, meaning that a determination of Mohs' hardness number for a mineral is based upon scratch tests. For example, gypsum (Mohs' hardness number 2) will scratch talc (Mohs' hardness number 1). Talc, however, will not scratch gypsum. **Glass** is assigned a Mohs hardness number of 5.5 because it will scratch apatite (Mohs' hardness number 5) but will not scratch orthoclase feldspar (Mohs' hardness number 6).

Scratch tests are a common method used to identify mineral hardness relative to Mohs' scale. Streak tests are often carried out on streak plates. Mineral hardness is a fundamental property of minerals and can be used to identify unknown minerals. In the absence of comparative minerals, geologists often resort to common objects with a relatively well-established Mohs' hardness number. In addition to glass (5.5), copper pennies measure 3.5, and the average human fingernail averages a Mohs' hardness of 2.5.

The Mohs' scale is a comparative index rather than a linear scale. In fact, Mohs' scale has a near logarithmic relationship to absolute hardness. At the lower, softer end of the scale, the difference in hardness is close to linear, but at the extremes of harness, there are much greater increases in absolute hardness (e.g., a greater increase in the hardness between corundum and diamond than between quartz and topaz).

Hardness is a property of minerals derived from the nature and strength of chemical bonds in and between **crystals**. The number of atoms and the spatial density of bonds also influences mineral hardness. Softer minerals are held together by weak van der Waals bonds. The hardest minerals tend to be composed of dense arrays of atoms covalently bonded together.

Hardness characteristics—especially in calcite crystals—may vary as a property dependent upon the direction of the scratch (i.e., able show evidence of a particular Mohs' number if scratched along one face or direction as opposed to a different hardness number if scratched in a different direction).

See also Chemical bonds and physical properties; Field methods in geology; Mineralogy

MOLINA, MARIO (1943-)

Mexican-born American chemist

Mario Molina is an important figure in the development of a scientific understanding of the atmosphere. Molina earned national prominence by theorizing, with fellow chemist **F. Sherwood Rowland**, that chlorofluorocarbons (CFCs) deplete the earth's ozone layer. Molina and Sherwood shared the 1995 Nobel Prize in chemistry, along with the Dutch chemist Paul Crutzen, for their work on the depletion of **ozone** in the atmosphere. In his years as a researcher at the Jet Propulsion Lab at the California Institute for Technology (CalTech) and a professor at the Massachusetts Institute of Technology (MIT), Molina has continued his investigations into the effects of chemicals on the atmosphere.

Mario José Molina was born in Mexico City to Roberto Molina-Pasquel and Leonor Henriquez. Following his early schooling in Mexico, he graduated from the Universidad Nacional Autónoma de México in 1965 with a degree in chemical engineering. Immediately upon graduation, Molina went to West Germany to continue his studies at the University of Freiburg, acquiring the equivalent of his master's degree in polymerization kinetics in 1967. Molina then returned to Mexico to accept a position as assistant professor in the chemical engineering department at his alma mater, the Universidad Nacional Autónoma de México.

In 1968, Molina left Mexico to further his studies in physical chemistry at the University of California at Berkeley. He received his Ph.D. in 1972 and became a postdoctoral associate that same year. His primary **area** of postdoctoral work was the chemical laser measurements of vibrational energy distributions during certain chemical reactions. The following year, 1973, was a turning point in Molina's life. In addition to marrying a fellow chemist, Luisa Y. Tan, Molina left Berkeley to continue his postdoctoral work with physical chemist, Professor F. Sherwood Rowland, at the University of California at Irvine.

Both Molina and Rowland shared a common interest in the effects of chemicals on the atmosphere. Both were also well aware that every year millions of tons of industrial pollutants were bilged into the atmosphere. They also had questions about emissions of nitrogen compounds from supersonic aircraft. Molina and Rowland decided to conduct experiments to determine what happens to chemical pollutants that reach both the atmosphere directly above us but also at stratospheric levels, some 10–20 mi (16–32 km) above the earth. Both men knew that within the **stratosphere**, a thin, diffuse layer of ozone gas encircles the planet, which acts as a filter screening out much of the Sun's most damaging ultraviolet radiation. Without this ozone shield, life could not survive in its present incarnation.

They concentrated their research on the impact of a specific group of chemicals called chlorofluorocarbons, which are widely used in such industrial and consumer products as aerosol spray cans, pressurized containers, etc. They found that when CFCs are subjected to massive ultraviolet radiation they break down into their constituent chemicals: chlorine, fluorine, and **carbon**. It was the impact of chlorine on ozone that alarmed the two scientists. They found that each chlorine **atom** could destroy as many as 100,000 ozone molecules before becoming inactive. With the rapid production of CFCs for commercial and industrial use, millions of tons annually, Molina and Rowland were alarmed that the impact of CFCs on the delicate ozone layer within the stratosphere could be life-threatening.

Mario Molina published the results of his and Rowland's research in *Nature* magazine in 1974. Their findings had startling results. Molina was invited to testify before the United States House of Representative's Subcommittee on Public Health and Environment. Suddenly CFCs were a popular topic of conversation. Manufacturers began searching for alternative propellant gases for their products.

Over the next several years, Molina refined his work and, with Rowland, published additional data on CFCs and the destruction of the ozone layer in such publications as *Journal of Physical Chemistry*, *Geophysical Research Letter,* and in a detailed piece entitled "The Ozone Question" in *Science*. In 1976, Mario Molina was named to the National Science Foundation's Oversight Committee on Fluorocarbon Technology Assessment.

In 1982, Molina became a member of the technical staff at the Jet Propulsion Laboratory at CalTech; two years later he was named senior research scientist, a position he held for an additional five years. In 1989, Mario Molina left the West Coast to accept the dual position of professor of **atmospheric chemistry** at the MIT's department of Earth, atmosphere and planetary sciences, and professor in the department of chemistry. In 1990, he was one of 10 environmental scientists awarded grants of $150,000 from the Pew Charitable Trusts Scholars Program in Conservation and the Environment. In 1993, he was selected to be the first holder of a chair at MIT established by the Martin Foundation, Inc., "to support research and education activities related to the studies of the environment."

Molina has published more than fifty scientific papers, the majority dealing with his work on the ozone layer and the chemistry of the atmosphere. In 1992, Molina and his wife, Luisa, wrote a monograph entitled "Stratospheric Ozone" published in the book *The Science of Global Change: The Impact of Human Activities on the Environment* published by the American Chemical Society.

His later work has also focused on the atmosphere-biosphere interface which Molina believes is "critical to understanding global climate change processes." He is the recipient of more than a dozen awards including the 1987 American Chemical Society Esselen Award, the 1988 American Association for the Advancement of Science Newcomb-Cleveland Prize, the 1989 NASA Medal for Exceptional Scientific Advancement, and the 1989 United Nations Environmental Program Global 500 Award.

See also Atmospheric circulation; Atmospheric composition and structure; Atmospheric pollution

MONOCLINE

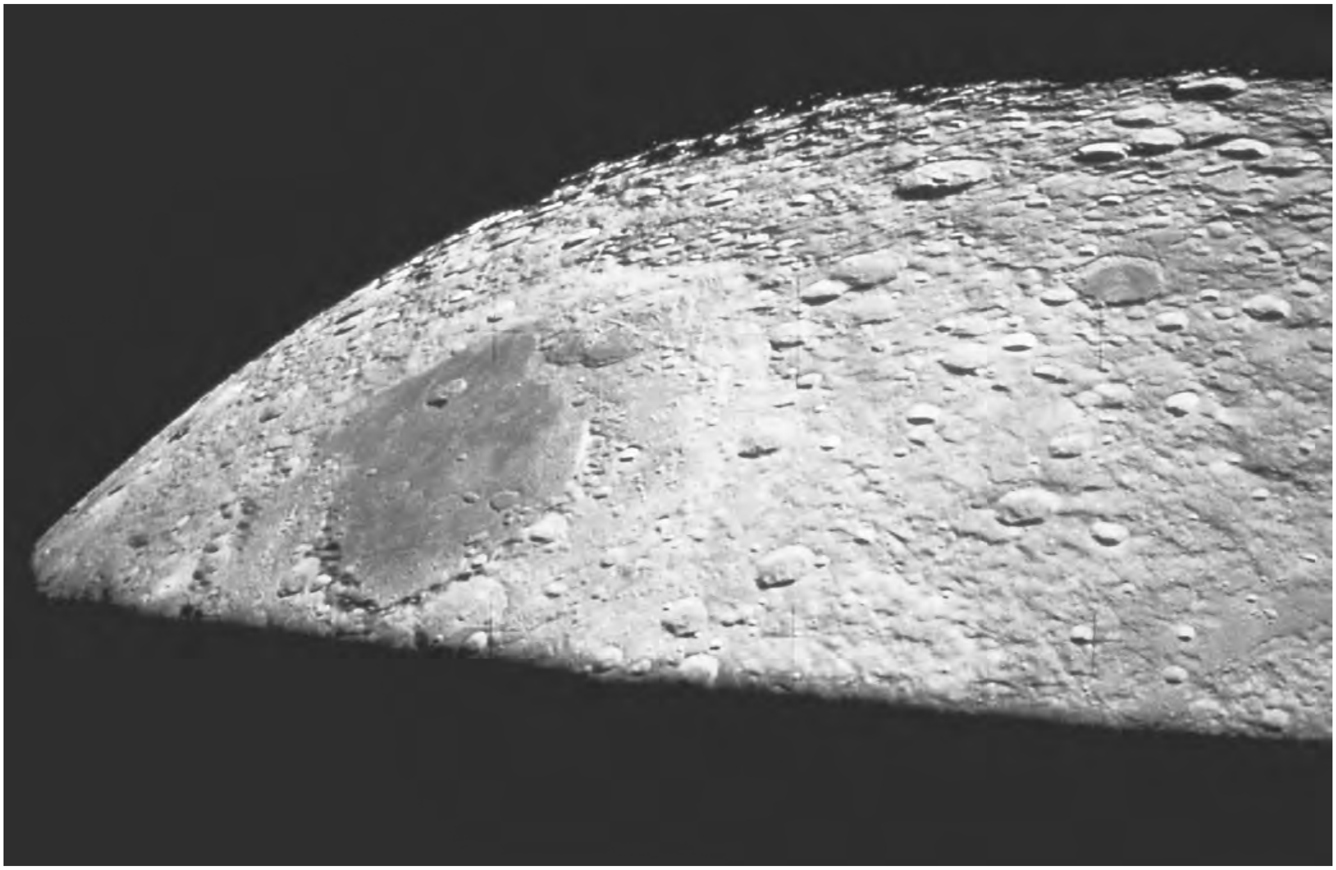
Monoclines are **folds** consisting of two horizontal (or nearly so) limbs connected by a shorter inclined limb. They can be compared to anticlines, which consist of two inclined limbs dipping away from each other, and synclines, which consist of two inclined limbs dipping towards each other.

Folds such as monoclines, anticlines, and synclines are defined solely on the basis of their geometry, and the names therefore have no genetic connotations. Monoclines are, however, characteristic of regions in which **sedimentary rocks** have been deformed by **dip** slip movement along vertical or steeply dipping faults in older and deeper rocks, such as the Colorado Plateau of the southwestern United States. An excellent example of a Colorado Plateau monocline is the Waterpocket fold in Capitol Reef National Park. Most monoclines are classified as drape folds or forced folds because the sedimentary rocks are draped or forced as a result of movement along the underlying faults. Drape folds and forced folds are not necessarily monoclinal, though, so care must be taken to distinguish between geometric and genetic names.

The shape of a monoclinal drape fold is controlled in part by the nature of the underlying fault (normal, reverse, or vertical) and in part by the mechanical nature of the strata being folded. A sequence of relatively thin strata, for example, is less resistant to folding than a single **rock** unit of the same aggregate thickness. Thick rock units such as massive sandstones may fracture during monoclinal folding because they are too stiff to be bent without breaking, whereas rock units such as shales may be easily folded because they consist of innumerable and thin laminae that are weakly bonded to each other. Likewise, the rock type of the lowermost layer being folded has an influence on the form of the fold. A weak rock such as shale, salt, or **gypsum** can attenuate much of the movement along the underlying fault and reduce the amplitude of the resulting fold.

See also Faults and fractures; Syncline and anticline

MONSOON • *see* SEASONAL WINDS



The Moon's surface. ***U.S. National Aeronautics and Space Administration (NASA).***

MOON

The Moon is Earth's only natural **satellite**. Reflecting light from the **Sun**, the Moon is often the brightest object in the night sky.

The Moon orbits Earth at an average distance of approximately 240,000 miles (385,000 km). With **revolution and rotation** periods of approximately 27.32 Earth days, the Moon is in synchronous orbit about the earth. This synchronous orbit maintains a "near side" and "far side" of the Moon. The "near side" faces Earth, while the far side is not visible from Earth. Although Russian **space** probes—and later many American probes—took the first pictures of the far side of the Moon years earlier, it was not until the flight of *Apollo 8* that United States astronauts became the first humans to directly view the far side of the Moon.

Orbital dynamics between the Sun, Moon, and Earth cause different patterns of illumination on the surface of the Moon as seen from Earth. As the Moon revolves about the earth, it appears to go through a series of illumination phases. The Sun constantly illuminates one-half of the lunar surface. The changing orientation in the three body system (Sun, Earth, and Moon), changes to what extent that solar illumination covers areas on the surface of the Moon that are visible from Earth.

Because the earth is revolving about the Sun, the displacement of the earth along it's orbital path establishes the time it takes to complete a cycle of lunar phases—a synodic month—and return the Sun, Earth, and Moon to the same starting alignment. This synodic month is approximately 29.5 days, and is longer than the 27.32-day sideral month.

A waxing moon is one where the **area** illuminated increases each night. A waning moon describes a decreasing area of illumination.

The Moon's phases are a cyclic repetition of illumination patterns described as: new moon, waxing crescent moon, waxing half moon, waxing gibbous moon, full moon, waning gibbous moon, waning half moon, waning crescent moon, followed by a return to the new moon phase.

A new moon occurs when the Moon's orbital path places it between the earth and the Sun. Only the side of the Moon not visible to Earth is illuminated and the Moon is lost in the bright sunlight. Occasionally when the Moon is also in the proper plane of alignment, it may provide a full or partial solar **eclipse** over portions of Earth's surface.

Relative to the Sun and starfield, the Moon appears to move eastward. Following the new moon, the next night, a small sliver or crescent becomes illuminated. The waxing crescent moon is low on the western horizon and is visible just after sunset (i.e., the Moon "sets" shortly after sunset).

As the orbital dynamics shift, the crescent grows larger—and the Moon sets later—each night following sunset. Approximately one week following the new moon, the Moon is one quarter of the way through it's orbital revolution of Earth, and one half of the lunar surface is illuminated as a waxing half moon. Depending upon **latitude**, the waxing half moon appears nearly directly overhead (at the zenith of the celestial meridian) at sunset. The waxing half moon will set about midnight local time. During the next week, the area of the Moon reflecting sunlight to Earth covers more than half of the visible lunar surface, and is described as a waxing gibbous moon.

Approximately two weeks after the new moon, the visible surface of the Moon becomes fully illuminated because the Moon is on the opposite side of Earth relative to the Sun. If the earth and Moon are in the proper plane, Earth may actually block the Sun's light over a portion of the lunar surface and cause a partial to full lunar eclipse. The full moon rises at sunset and sets at dawn.

Following the full moon, the Moon begin to progressively darken through waning gibbous phases until about a week following the full moon it forms a waning half moon. The waning half moon rises about midnight and sets about noon the next day. Continued darkening over the last week of the lunar cycle provides a waning crescent moon that finally returns full cycle to the new moon state, where the Moon and Sun, on the same side of Earth's orbit about the Sun, appear to rise and set together.

The phases of the Moon proved one of the most fundamental astronomical calendars for ancient peoples and the ancient Greek astronomers asserted that the Moon reflected the Sun's light. Phases of the Moon remain critical in determining the date and timing of many religious observances (e.g., Passover, Easter, Ramadan, Visakha Puja, etc.)

Because the earth is larger than the Moon and relatively close to the Moon, it casts a large shadow that causes lunar eclipses. Solar eclipses (where the Moon blocks the Sun) are less frequent and are only possible because, although the Sun is much larger than the Moon, the Moon is much closer to Earth. The present set of orbital dynamics and distances allow solar eclipses because the Sun and Moon have the same angular size (approximately 0.5°) when viewed from Earth. The average human thumb, held out at arm's length obscures approximately 0.5° degrees and will thus, block both the Sun and Moon. (*Warning: Direct viewing of the Sun may cause blindness or optic injury and should not be attempted. Solar observation requires special protective goggles that filter and reduce the intensity of sunlight.*)

The Moon appears to shift its position eastward on the celestial sphere by approximately 13° per night (i.e., appears to move 13° to the east from its prior position if observed at the same time on successive nights).

The Moon is nearly spherical with polar and equatorial radii varying by about a mile. The equatorial radius of the Moon is approximately 1,080 miles (1,738 km). The diurnal temperatures (the day/night temperatures) on the Moon range from approximately –280°F to +260°F (–173°C to +126°C). Contrary to popular belief, the Moon does have a thin atmosphere that consists of helium, argon, methane, minute amounts of **oxygen**, and other trace elements. The density of the lunar atmosphere is only approximately 2×10^5 particles/cm^3 and results in a lunar **atmospheric pressure** of only 8.86×10^{-14} inHg (3×10^{-12} mb) in contrast to Earth's average surface atmospheric pressure of 29.92 inHg (1,014 mb).

The thin and dry lunar atmosphere provides no substantial **weathering** agents (e.g., **wind**, **water**, etc.) and so erosional processes are greatly slowed—essentially reduced to heating, cooling, and slow geochemical changes. The thin atmosphere also offers no protection from meteor impacts and the combination of lack of protection and lack of Earth-like **erosion** produces a heavily cratered lunar landscape that preserves billions of years of accumulated impact craters.

Although the Moon is a quarter of Earth's size, it has only approximately 1.2% of Earth's mass. The gravitational attraction at the surface of the Moon is about one-sixth that of the gravitational attraction at Earth's surface. Accordingly, neglecting air friction (something easily accomplished on the Moon but not on Earth) an object in freefall near Earth's surface accelerates at 9.8 m/s^2, but near the lunar surface, the acceleration due to gravity is approximately 1.62 m/s^2.

See also Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Diurnal cycles; Earth (planet); History of manned space exploration; Gravity and the gravitational field; Solar system

MORAINES

Moraines are glacial deposits of **till** (sediment) that are classified by their position relative to the glacial **ice** sheet. Moraines are classified as terminal moraines, lateral moraines, medial moraines, or ground moraines.

Moraines are formed of the sedimentary materials of varying sizes. Accordingly, they are poorly sorted and are essentially the sedimentary "dump" of material broken, dislodged, smashed, ground, and then deposited during the movement of **glaciers**.

End moraines form at the end of the glacial sheet. The end moraine that forms the maximum of glacial extent of glacial coverage (i.e., the farthest extent of "movement" of the glacier) is termed the terminal moraine.

Lateral moraines are deposits of till that accumulate along the lateral margins of the glacial sheet. As glacial sheets fuse, the corresponding fusion of lateral moraines forms a medial moraine.

Ground moraines form from deposits beneath the glacial sheet.

Moraines are geomorphologic features that can last long after glacial retreat (i.e., glacial **melting**) and moraines often form the base for varied and hilly landscapes in areas subject to periodic **glaciation**. Moraines can themselves be reshaped by subsequent glaciations and thus moraine patterns are often used to determine the extent and pattern of glaciations from which further information regarding climate changes can be derived.

See also Archeological mapping; Fjords; Ice ages; Ice heaving and ice wedging; Landforms; Landscape evolution; Topography and topographic maps

MORLEY, EDWARD WILLIAMS
(1838-1923)
American physicist

Originally trained for the ministry, Edward Williams Morley decided instead in 1868 to pursue a career in science, the other great love of his life. Initially, Morley devoted himself primarily to teaching, but gradually became engaged in original research. His work can be divided into three major categories: the first two involved the determination of the **oxygen** content of the atmosphere and efforts to evaluate Prout's hypothesis. His third field of research involved experiments on the velocity of light, and it was this research that brought him scientific notoriety.

Morley was born in Newark, New Jersey, on January 29, 1838. His mother was the former Anna Clarissa Treat, a schoolteacher, and his father was Sardis Brewster Morley, a Congregational minister. According to a biographical sketch of Morley in the December 1987 issue of the *Physics Teacher*, the Morley family had come to the United States in early Colonial days and "was noted for its deep patriotism and religious devotion."

Morley's early education took place entirely at home, and he first entered a formal classroom at the age of nineteen when he was admitted to Williams College in Williamston, Massachusetts, as a sophomore. His plans were to study for the ministry and to follow his father in a religious vocation. He also took a variety of courses in science and mathematics, including **astronomy**, **chemistry**, calculus, and optics. His courses at Williams were a continuation of an interest in science that he had developed at home as a young boy.

Morley graduated from Williams as valedictorian of his class with a bachelor of arts degree in 1860. He then stayed on for a year to do astronomical research with Albert Hopkins. Morley's biographers allude to the careful and precise calculations required in this work as typical of the kind of research Morley most enjoyed doing.

After completing his work with Hopkins, Morley entered the Andover Theological Seminary to complete his preparation for the ministry, while concurrently earning his master's degree from Williams. Morley graduated from Andover in 1864, but rather than finding a church, he took a job at the Sanitary Commission at Fortress Monroe in Virginia. There he worked with Union soldiers wounded in the Civil War.

His work completed at Fortress Monroe, Morley returned to Andover for a year and then, failing to find a ministerial position, took a job teaching science at the South Berkshire Academy in Marlboro, Massachusetts. It was at Marlboro that Morley met his future wife, Isabella Birdsall. The couple was married in 1868. Morley had finally received an offer in September, 1868, to become minister at the Congregational church in Twinsburg, Ohio. He accepted the offer but, according to biographers David D. Skwire and Laurence J. Badar in the *Physics Teacher*, became disenchanted with "the low salary and rustic atmosphere" at Twinsburg and quickly made a crucial decision: he would leave the ministry and devote his life to science.

The opportunity to make such a change had presented itself shortly after Morley arrived in Twinsburg when he was offered a position teaching chemistry, botany, **geology**, and **mineralogy** at Western Reserve College in Hudson, Ohio. Morley accepted, and when Western Reserve was moved to Cleveland in 1882, Morley followed. While still in Hudson, Morley was assigned to a full teaching load, but still managed to carry out his first major research project. That project involved a test of the so-called Loomis hypothesis, which held that during periods of high **atmospheric pressure**, air is carried from upper parts of the atmosphere to the earth's surface. Morley made precise measurements of the oxygen content in air for 110 consecutive days, and his results appeared to confirm the theory.

In Cleveland, Morley became involved in two important research studies almost simultaneously. The first was an effort at obtaining a precise value for the atomic weight of oxygen, in order to evaluate a well-known hypothesis proposed by the English chemist William Prout in 1815. Prout had suggested that all atoms are constructed of various combinations of hydrogen atoms.

Morley (as well as many other scientists) reasoned that should this hypothesis by true, the atomic weight of oxygen (and other elements) must be some integral multiple of that of hydrogen. For more than a decade, Morley carried out very precise measurement of the ratios in which oxygen and hydrogen combine and of the densities of the two gases. He reported in 1895 that the atomic weight of oxygen was 15.897, a result that he contended invalidated Prout's hypothesis.

Even better known than his oxygen research, however, was a line of study carried out by Morley in collaboration with Albert A. Michelson, professor of **physics** at the Case School of Applied Science, adjacent to Western Reserve's new campus in Cleveland. Morley and Michelson designed and carried out a series of experiments on the velocity of light. The most famous of those experiments were designed to test the hypothesis that light travels with different velocities depending on the direction in which it moves, a hypothesis required by current theories regarding the way light is transmitted through **space**. A positive result for that experiment was expected and would have confirmed existing beliefs that the transmission of light is made possible by an invisible "ether" that permeates all of space.

In 1886, Michelson and Morley published their report of what has become known as the most famous of all negative experiments. They found no difference in the velocity with which light travels, no matter what direction the observation is made. That result caused a dramatic and fundamental rethinking of many basic concepts in physics and provided a critical piece of data for Albert Einstein's theory of relativity.

The research on oxygen and the velocity of light were the high points of Morley's scientific career. After many years of intense research, Morley's health began to deteriorate. To recover, he took a leave of absence from Western Reserve for a year in 1895 and traveled to **Europe** with his wife. When he returned to Cleveland, he found that his laboratory had been dismantled and some of his equipment had been destroyed. Although he remained at Western Reserve for another decade, he never again regained the enthusiasm for research that he had had before his vacation.

Morley died on February 24, 1923, in West Hartford, Connecticut, where he and Isabella had moved after his retirement in 1906; she predeceased him by only three weeks. Morley was nominated for the Nobel Prize in chemistry in 1902, and received a number of other honors including the Davy Medal of the Royal Society in 1907, the Elliot Cresson Medal of the Franklin Institute in 1912, and the Willard Gibbs Medal of the Chicago section of the American Chemical Society in 1917. He served as president of the American Association for the Advancement of Science in 1895 and of the American Chemical Society in 1899.

See also Atmospheric chemistry; Atmospheric composition and structure; Quantum theory and mechanics

MORLEY, LAWRENCE WHITAKER
(1920-)

Canadian geologist

Lawrence Morley has had a long, successful career in geophysics, including work on **remote sensing**, aerophysics, palaeomagnetic research, and geophysical instrumentation and interpretation, publishing 65 scientific and technical papers. Born in Toronto, Ontario, Morley received his education at Collingwood, Owen Sound and Lakefield College School, Ontario. He then attended the University of Toronto, studying **Physics** and Geology, but his degree was interrupted by the Second World War, during which time he served four years with the Royal Navy as a radar officer. Morley graduated in 1946, after hostilities had ended. In 1949, Morley returned to the University of Toronto to complete a Masters and then a Ph.D. in geophysics, during which time he studied palaeomagnetism under Professor **J. Tuzo Wilson**.

Morley was the first to suggest the theory of the magnetic imprinting of rocks on the ocean floor in 1963, during a talk to the Royal Society of Canada. Previously in 1915, Alfred Wegner (1880–1930) had proposed that there had once been a super-continent, which he named Pangaea, that had slowly moved apart. However, Wegner's theory could not explain how such movement occurred, and his theory was largely ignored. In the early 1960s, Harry Hess (1906–1969) and Robert Dietz both independently hypothesized that that seafloor spreading was responsible for the motion of the continents. It had long been known that the earth had undergone a number of magnetic reversals in its long history. Morley suggested that new **lava** emerging from an ocean ridge would produce **rock** fixed in the current **magnetic field** of Earth. Rocks older than the last magnetic reversal would have an opposing polarity. These should appear as parallel stripes on both sides of an ocean ridge.

However, a paper submitted to the journal *Nature* was rejected, as was an article given to the *Journal of Geophysical Research*. By the time his ideas appeared in a special publication of the Royal Society of Canada, in 1964, Frederick J. Vine (1939–) and **Drummond Matthews** (1931–), working independently, had already published the same hypothesis. While the theory of magnetic striping in the earth's **crust** is sometimes referred to as the Vine-Matthews-Morley Hypothesis, just as often Morley's name is omitted. Surveys in the mid-1960s found the expected stripes at every ocean ridge. This evidence confirmed the ideas of Wegner, Dietz and Hess, and resulted in a revolution in **Earth science**, giving rise to the theory of **plate tectonics**.

Morley did pioneering work on aerial mineral and **petroleum** surveys using the airborne magnetometer in the 1940s, working in Venezuela, Columbia, and Canada. He was appointed to the Geological Survey of Canada in 1952, where he served for 17 years as Chief of the Geophysics Division to the Geological Survey. He promoted the Federal/Provincial Aeromagnetic Survey Program, which eventually covered the whole of Canada, producing more than 7,000 detailed maps. Much of his work was aimed at finding mineral and petroleum deposits, and he directed the surveying of Hudson's Bay and the Canadian offshore regions for oil reserves.

With Lee Godby, Morley helped establish the Canada Centre for Remote Sensing and was its founding Director-General from 1971 to 1980. He also served with the Canadian High Commission in London, England as its Science Counselor. Morley was consulted by York University to promote a University/Industry Institute for Space Research, becoming the founding Executive Director of the Institute for Space and Terrestrial Science in 1986. In the 1980s, Morley formed a consulting company specializing in remote sensing and geophysical exploration, and since 1990, this has been his main focus.

Morley is a fellow of the Royal Society of Canada and the Canadian Aeronaut and Space Institute, as well as being a member of the Society for Explorational Geophysics, the American Geophysics Union, the American Society of Photogrammetry and Remote Sensing, and the Canadian Institute of Surveys and Mapping. Morley has received a number of honors, including the McCurdy medal (1974), and the Tuzo Wilson Prize (1980).

See also Plate tectonics; Sea-floor spreading

MOSANDER, CARL GUSTAF (1797-1858)

Swedish chemist

In a large part, credit for unraveling the complex nature of the rare Earth elements goes to Carl Gustaf Mosander. Mosander was born in Kalmar, Sweden, on September 10, 1797. He was educated as a physician and pharmacist and served as an army surgeon for many years.

Mossander's most important professional association was with the eminent Swedish chemist J. J. Berzelius. Mosander lived with Professor and Mrs. Berzelius for many years and worked as Berzelius' assistant at the Stockholm Academy of Sciences. Eventually, Mosander became curator of **minerals** at the Academy and, in 1832, succeeded Berzelius as Permanent Secretary of the Academy. Mosander was also Professor of **Chemistry** and **Mineralogy** at the Caroline Institute for many years.

Mosander became interested in the rare Earth elements in the late 1830s. Fifty years earlier, a Swedish army officer, Carl Axel Arrhenius, had discovered a new mineral near the small town of Ytterby that he named ytterite. Chemists spent much of the next century trying to separate the mineral into its many chemically-similar parts.

The first breakthrough in this effort occurred in 1794 when Johan Gadolin (1760–1852) showed that ytterite contained a large fraction of a new oxide, which he called yttria. A decade later, M. H. Klaproth, Berzelius, and Wilhelm Hisinger (1766–1852) showed that ytterite also contained a second oxide, which they termed ceria.

Mosander first concentrated his efforts on the ceria component of ytterite. In 1839, he found that the ceria contained a new element, which he named lanthanum (for hidden). Mosander did not publish his results immediately, however, because he was convinced that yet more discoveries were to be made. He was not disappointed in these hopes. In 1841, he identified a second new component of ceria. He named the component didymium, for twin, because it was so closely related to lanthanum. Later research showed that didymium was not itself an element, but a complex mixture of other rare earth elements.

In 1843, Mosander turned his attention to the yttria component of ytterite. He was able to show that the yttria consisted of at least three components. He kept the name yttria for one and called the other two erbia and terbia. The last two of these components are now known by their modern names of erbium and terbium. Mosander is acknowledged as the discoverer, then, of three elements: lanthanum, erbium, and terbium. Mosander died in Ångsholm, Sweden, on October 15, 1858.

See also Chemical elements

MOUNTAIN CHAINS

Mountain chains are elongate, elevated areas of the earth's surface comprising several sub-parallel mountain ranges. Each mountain range is a connected series of mountain peaks (i.e., large **rock** masses that rise abruptly above the surrounding landscape). Mountain chains may be a thousand or more kilometers long and hundreds of kilometers wide. Mountain chains are formed by the interplay of endogenic and exogenic processes. Endogenic processes are those that originate within the earth, such as orogenesis and volcanism. Exogenic processes are external processes, such as **weathering** and **erosion** due to the action of **water**, **ice**, and **wind**.

Volcanism during subduction of oceanic **crust** beneath oceanic crust creates an island arc. **Island arcs** may comprise an arcuate alignment of volcanic island peaks (e.g., the Aleutian Islands) or a continuous land **area** comprising a central mountain chain formed by volcanic and tectonic processes (e.g., Japan). Subduction of oceanic crust beneath continental crust creates a Cordilleran or Andean-style mountain chain. The best-known example is the Andes in **South America**, where the oceanic Nazca Plate is subducted beneath the continental South American Plate. In the Barisan Mountains of Sumatra, Indonesia, oceanic **lithosphere** of the Indo-Australian Plate is obliquely subducted beneath continental crust of the Sunda Plate. A network of faults comprising a transcurrent fault system dissects the resulting volcanic mountain chain.

Collisional mountain chains result from the collision between two continental **lithospheric plates** or between a continental plate and an island arc. The continental lithosphere is greatly thickened in this process called orogenesis. The resulting belt of uplifted crust forms a mountain chain with a commensurate deep lithospheric keel or root. Such isostatic balance can be likened to an iceberg where only a proportion protrudes out of the water, with a large part of its mass being below water. When material in the mountain is removed by erosion or tectonically through extensional faulting, compensatory uplift will occur while the lithospheric root remains. Rocks previously at greater depths are, therefore, brought closer to the surface in a process called exhumation. Tens of kilometers of rock may be removed by erosion before a collisional mountain chain is eventually flattened. Eroded sediments are deposited in adjacent extensional or foreland basins. Extensive erosion plus or minus tectonic exhumation due to displacement along faults results in exhumation of high-grade rocks. Collisional mountain belts include:

- the European Alps, formed by collision of the European Plate with the Adriatic Plate following closure of part of the Tethyan Ocean,
- the Himalayas, formed by the collision between the Eurasian Plate with island arcs and the Indian Plate.

Folding of rock layers may also occur in the hinterland to a collisional orogenic belt or in a cover sequence where basement rocks slide past one another at the same time as undergoing regional shortening (i.e., a transpressional belt). Trains of **folds** can also form during gravitationally induced sliding on a weak basal décollement horizon without regional shortening. In all such folded areas, rock layers more resistant to erosion in regional-scale antiforms may define a continuous mountain range along each **anticline**. Such fold mountain chains generally lack the presence of a deep lithospheric root and will more rapidly disappear due to the effects of erosion over time.

Steep to moderately dipping normal faults formed during regional, horizontal extension during collapse of a collisional mountain belt or **rifting** may downthrow blocks of rock called graben, leaving elongate, fault-bounded high blocks (horsts). Block-faulted mountain chains are formed if displacements are great enough and erosion rates are low. Rock layers between parallel-dipping normal faults are tilted and this may result in asymmetrical mountain ranges with steep faces and

Mount Everest is the tallest mountain of the tallest, and youngest, mountain chain in the world, the Himalayas. ***Archive Photos. Reproduced by permission.***

long **dip** slopes parallel to layering. Valleys along intervening graben in which the eroded sediments are deposited separate the ridges. Mountain chains formed by extensional faulting occur in areas of widely distributed extension, such as the Basin and Range Province of Utah and Wyoming. Displacement can also take place along shallowly dipping extensional detachment faults that widen to form ductile **shear zones** at greater depth. The earth's lithosphere is thinned during regional extension. In order to compensate for this, the underlying **asthenosphere** is arched upward beneath the area of greatest lithospheric thinning. Extensional detachments are folded and deep crustal rocks exhumed, forming metamorphic core complexes. Metamorphic core complexes commonly produce elongate domal mountains as their metamorphic and possibly igneous core is likely to be more resistant to subsequent weathering than the surrounding low-grade rocks.

See also Orogeny; Plate tectonics; Subduction zone

MOUNTAIN FORMATION • *see* OROGENY

MT. PINATUBO VOLCANIC ERUPTION • *see* VOLCANIC ERUPTIONS

MT. ST. HELENS VOLCANIC ERUPTION • *see* VOLCANIC ERUPTIONS

MUD FLOW

The term mud flow, although not part of the classification system used by most **landslide** specialists, is a form of **mass movement** or **mass wasting** widely used in a manner that is synonymous with wet to very wet, rapid to extremely rapid earth flow. Mud itself is defined by most geologists as an unlithified mixture of silt, **clay**, and **water**; therefore, a mud flow is a flow consisting primarily of silt, clay, water, and other minor constituents such as **sand**, cobbles, boulders, trees, and other objects. A flow in which mud is a minor constituent relative to sand-size or coarser particles is by definition a **debris flow** or, if large pieces of **bedrock** are involved, a **rock** flow.

Because volcanic ash deposits commonly **weather** into clayey materials, mud flows are common on and around volcanoes as well as areas covered by deposits of fine-grained volcanic ash known as loess. A mudflow on a **volcano** can also be referred to as a fine-grained or muddy **lahar**.

Like debris flows, mud or earth flows can begin by mobilization from a landslide, incorporation of muddy sediments into flooding, or rapid **melting** of snow and **ice** during a volcanic eruption. Regardless of their mode of origin, mud or earth flows can be dangerous and destructive because of their great density (typically more than 50% solid material) and velocity. The density of debris and mudflows also allows them to transport unusually large boulders compared to **floods** consisting primarily of water. A typical debris or mudflow consisting of 60% solids and 40% water would have a density of about 125 lb/ft^3 (2,000 kg/m^3), or twice that of water. Thus, the buoyant force exerted on a boulder by a mud or debris flow would be about twice that exerted on the same boulder by water.

See also Floods

MUIR, JOHN (1838-1914)

Scottish-born American naturalist

John Muir—naturalist, conservationist, mountaineer, and chronicler of the American frontier—was born in Dunbar, Scotland on April 21, 1838. During his lifetime, Muir published more than 300 articles and 10 books recounting his travels, scientific observations, and opinions on nature conservation. His wanderlust led him on expeditions around the globe, but California's Sierra Nevadas were his home. In addition to his descriptive and inspirational nature writing, Muir advanced a number of scientific theories, including the now-accepted hypothesis that **glaciers** carved Yosemite Valley. His love of the Sierras, and his concern for their preservation, led him to become one of America's first environmental activists. Muir co-founded the Sierra Club in 1871, and he served as the club's first president until his death in 1914.

John Muir immigrated to Fountain Lake, Wisconsin in 1849 with his family at age 11. The Muir family's hard-working frontier life left John no time to continue the formal schooling he had begun in Scotland. He did, however, maintain his passion for reading and natural science, and excursions into the woods provided a welcome diversion from his father's strict discipline and grueling work schedule. John put his self-taught knowledge to use at the Muir homestead by inventing an assortment of machines, including a table saw and a machine that dumped him out of bed for morning chores.

In 1860, John Muir left home at age 22 to exhibit his inventions at the Wisconsin state fair in Madison. There he received his first public recognition in the form of a *Wisconsin State Journal* article describing his prize-winning whittled clocks. He also met one of the exhibit judges, Mrs. Jeanne Carr, and her husband, Dr. Ezra Carr, a professor at the University of Wisconsin, who would become his lifelong friends and mentors. Muir attended classes at the University of Wisconsin from 1861 until 1863 when a lack of funds and the Civil War draft led him to return home.

No letter came from the draft board, and Muir set out on a summer plant-collecting trip that became a four-year walking expedition into Canada. He financed his botanical studies with a series of factory jobs and contributing his inventions to improve production along the way. In spring of 1867, Muir suffered a blinding eye injury at a carriage factory in Indianapolis. When his sight returned after a month of painful recovery, he decided to devote his newly regained vision to observations of nature. After a visit home, Muir walked 1,000 mi (1,609 km) to the **Gulf of Mexico**, and boarded a ship to Cuba, New York, and finally Panama. He traveled across the Isthmus, and sailed on to California. John Muir was 30 when he arrived in San Francisco in March of 1868.

From San Francisco, Muir walked east across the San Joaquin Valley. He described his first impression of the Sierras in his book, *My First Summer in the Sierra*: "...from the eastern boundary of this vast golden flower-bed rose the mighty Sierra, miles in height, and so gloriously colored and so radiant, it seemed not clothed with light but wholly composed of it, like the wall of some celestial city.... Then it seemed to me that the Sierra should be called...the Range of Light." Muir spent the summer of 1869 herding sheep, or "hooved locusts" as he would later call them, at Tuolumne Meadows.

From 1869 until 1880, John Muir systematically explored the mountains of California from his cabin in Yosemite Valley. He traveled, unarmed, through the mountains carrying a tin cup, food, and a notebook. He observed active mountain glaciers, and hypothesized that the slow grinding of **ice** had carved Yosemite's soaring **granite** cliffs. His glacial theory, published in 1871 by the *New York Tribune,* gained him the respect of University of California geologist, Joseph LeConte, among others. His friends, the Carrs, moved to Oakland in 1869, and encouraged Muir to pursue his writing during this period. They also sent their influential academic friends to visit him in Yosemite, including Harvard botanist, Asa Gray, and, in May 1871, Ralph Waldo Emerson.

John Muir married Luisa Wanda Strentzel in 1880, and moved to Martinez, California to run the Strentzel's profitable fruit ranch, and help "Louie" raise their two daughters. Even during that 10-year period of relative domesticity, Muir continued to write and travel extensively, exploring Yellowstone, **Europe**, **Africa**, **Australia**, China, Japan, **South America**, and, of course, the Sierras. During the 1890s, he conducted a well-timed study of Alaska that coincided with the Klondike gold rush. His most popular book, *Stickeen,* is an account of a summer spent exploring Alaska's glaciers with a little black dog.

By the turn of the century, Muir had become a leading literary figure. His almost-spiritual descriptions of nature inspired influential and common people alike. Muir's articles in the *Century Magazine* gained him the attention and friendship of its like-minded editor, Robert Underwood Johnson. Their combined efforts led to an act of Congress that created Yosemite National Park in 1890. Muir and Johnson were subsequently involved in further conservation acts that resulted in the protection of Sequoia, Mount Rainier and Petrified Forest, and Grand **Canyon** National Parks. President Theodore Roosevelt visited Muir in Yosemite in 1901. Camping together in the shadow of El Capitan, they laid plans for the wilderness conservation programs that became Roosevelt's legacy.

In his last years, Muir turned his considerable energy to the preservation of wild lands. Muir, Johnson, and others formed the Sierra Club in 1892 to, as Muir wrote, "do something for wildness, and make the mountains glad.” The fight to prevent erection of a dam in Hetch Hetchy valley was one of the Sierra Club’s most dramatic early battles. Hetch Hetchy reservoir was filled in 1913, and Muir died, disappointed, on December 24, 1914 at the age of 76. His enduring legacy, however, were his books and essays that continue to inspire new generations of nature lovers and environmental activists. John Muir was America’s first environmentalist, and was perhaps America’s most influential naturalist.

See also Environmental pollution; Glacial landforms; History of exploration II (Age of exploration)

MURCHISON METEORITE

The Murchison meteorite was a meteorite that entered Earth’s atmosphere in September, 1969. The meteor fragmented before impact and remnants were recovered near Murchison, **Australia** (located about 60 mi [97 km] north of Melbourne). The fragments recovered dated to nearly five billion years ago—to the time greater than the estimated age of Earth. In addition to interest generated by the age of the meteorite, analysis of fragments revealed evidence of carbon-based compounds. The finds have fueled research into whether the organic compounds were formed from inorganic processes or are proof of extraterrestrial life dating to the time of Earth’s creation.

In particular, it was the discovery of amino acids and the percentages of the differing types of amino acids found in the meteorite (e.g., the number of left handed amino acids vs. right handed amino acids), that made plausible the apparent evidence of extraterrestrial organic processes as opposed to biological contamination by terrestrial sources.

If the compounds prove to be from extraterrestrial life, this would constitute a profound discovery that would have far-reaching global scientific and social impact concerning prevailing hypotheses about the **origin of life**. For example, some scientists, notably one of the discoverers of the structure of DNA, Sir Francis Crick, assert that in the period from the formation of Earth to the time of the deposition of the earliest discovered fossilized remains, there was insufficient time for evolutionary process to bring forth life in the abundance and variety demonstrated in the **fossil record**. Crick and others propose that a form of organic molecular “seeding” by meteorites exemplified by the Murchison meteorite (meteorites rich in complex **carbon** compounds) greatly reduced the time needed to develop life on Earth.

In fact, the proportions of the amino acids found in the Murchison meteorite approximated the proportions proposed to exist in the primitive atmosphere modeled in the **Miller-Urey experiment**. First conducted in 1953, University of Chicago researchers Stanley L. Miller and Harold C. Urey developed an experiment to test possible mechanisms in Earth’s primitive atmosphere that could have produced organic molecules from inorganic processes. Methane (CH_4), hydrogen (H_2), and ammonia (NH_3) gases were introduced into a moist environment above a water-containing flask. To simulate primitive **lightning** discharges, Miller supplied the system with electrical current. Within days organic compounds formed—including some amino acids. A classic experiment in molecular biology, the Miller-Urey experiment, established that the conditions that existed in Earth’s primitive atmosphere were sufficient to produce amino acids, the subunits of proteins comprising and required by living organisms. It is possible, however, that extraterrestrial organic molecules could have accelerated the formation of terrestrial organic molecules by serving a molecular templates.

In 1997, NASA scientists announced evidence that the Murchison meteorite contained microfossils that resemble microorganisms. The microfossils were discovered in fresh breaks of meteorite material. The potential finding remains the subject of intense scientific study and debate.

University of Texas scientists Robert Folk and F. Leo Lynch also announced the observation of **fossils** of terrestrial nanobacteria in another carbonaceous chondrite meteorite named the Allende meteorite. Other research has demonstrated that the Murchison and Murray meteorites (a carbonaceous chondrite meteorite found in Kentucky) contain sugars critical for the development of life.

See also Cosmology; Evolution, evidence of; Evolutionary mechanisms

MURCHISON, RODERICK (1792-1871)

Scottish geologist

Roderick Murchison was an amateur geologist of the Victorian age in Britain. Murchison’s paramount achievement is his naming of the periods of the stratigraphic column.

Murchison was wealthy and traveled often; both qualities enabled him to make a significant contribution to geological research in England and Wales while still an amateur in the field. Born in Ross in Scotland, Murchison was destined for a military career and trained at Durham and Great Marlow Military College. Until 1818, he lived in Ross-shire at which time he moved to England. A colleague, chemist Humphrey Davy, along with Murchison’s wife, persuaded Murchison to attend some lectures on **chemistry** and **geology**, and he then turned his vast energies to science.

Murchison named the Silurian System in 1839, after an **Iron** Age tribe in mid-Wales and the Permian in 1841, after the Perm region of Russia in the Ural Mountains. For his work on the Permian rocks of Russia, he was made an honorary member of the Academy and Natural History Society of St. Petersburg and Moscow. He named the **Devonian Period** with Adam Sedgwick after the British county of Devon. After great public arguments, however, Murchison and Sedgwick could not agree on the boundary between the Cambrian and the Silurian, and their friendship ended. Sedgwick had been mapping the Cambrian rocks of North Wales and the system is named after the Latin name for Wales. This famous controversy was not resolved until both men had gone to their graves as bitter enemies in the mid 1870s. Charles Lapworth resolved the crisis by naming the **Ordovician Period** (after another Iron Age Welsh tribe) between the Cambrian and Silurian.

In another scientific dispute, Murchison was against the theory of widespread **glaciation** as proposed by **Louis Agassiz** (1807–1873) and was one of the few geologists of his time who died not accepting it.

Murchison was knighted in 1846 following his presidency of the Geological Society of London in 1842 and his founding of the Royal Geographical Society (1830). He was subsequently four times the president of the later. When he died in 1871, he stipulated in his will that a medal and fund should be awarded each year by the Geological Society of London in his honor. It is awarded to outstanding Earth scientists who have shown a breadth and achievement over more than a narrow field. He was also a trustee of the British Museum. Murchison became the second Director-General of the Geological Survey of Great Britain in 1855, which gave him tremendous influence over the advancement of geology in Britain during the mid-Victorian age. He had little interest in economic geology such as hydrology, and this facet of geology did not develop at the survey during his time as Director-General. Historians debate that he actively prohibited research, but he certainly had an influence on slowing down work on the applied areas of geology. Murchison also founded a chair of geology and **mineralogy** at the University of Edinburgh.

See also Geologic time; Stratigraphy

N

Natural gas

Natural gas is a mixture of **hydrocarbons** (molecules that contain only **carbon** and hydrogen) and gases (most notably methane, ethane, propane, and butane) that exist naturally in rocks beneath the surface of the earth. It is widely used as a heating source, and in some cases, specific portions of the natural gas are used as starting materials in industrial processes. Natural gas is the product of the decaying of living matter over millions of years (as is also true for **petroleum**). Specific conditions, including low **oxygen** levels, are necessary for this to occur. The hydrocarbon gases are trapped in geological formations known as anticlines. Each of the major hydrocarbon components of natural gas is used as a fuel source.

Natural gas has its origins in decayed living matter, most likely as the result of the action of bacteria upon dead animal and plant material. In order for most bacteria to effectively break down organic matter to hydrocarbons, there must be low levels of oxygen present. This would mean that the decaying matter was buried (most likely under **water**) before it could be completely degraded to **carbon dioxide** and water. Conditions such as this are likely to have been met in coastal areas where **sedimentary rocks** and marine bacteria are common. The actions of heat and pressure along with bacteria produced a mixture of hydrocarbons. The smaller molecules which exist as gases were then either trapped in porous rocks or in underground reservoirs where they formed sources of hydrocarbon **fuels**.

Natural gas, like petroleum, is a mixture of many organic substances. The exact composition of different sources of natural gas varies slightly, but in all cases, methane is by far the most common component, with other hydrocarbons also being very common. Other gases such as oxygen, argon, and carbon dioxide make up the rest of most natural gas sources. The largest sources of natural gas in the United States are found in Alaska, Texas, Oklahoma, western Pennsylvania, and Ohio. It is estimated that the supply of natural gas in this country may be sufficient to last for two centuries—although the more readily accessible sources have been used, meaning that it will be more expensive to obtain natural gas in the future.

Natural gas is believed to have been first discovered and used by the Chinese, perhaps as early as 1000 B.C. Shallow stores of natural gas were released from just beneath the ground and piped short distances to be used as a fuel source. Natural gas could provide a continuous source of energy for flames. These "eternal fires" were found in temples and also used as attractions for visitors. In the 1800s, natural gas began to be piped short distances as a light source. With the discovery of oil in the 1860s, natural gas was largely ignored as a fuel source. One of the early difficulties with natural gas was in transporting it from the source to other sites for use. The combination of electric lights and petroleum meant that containers of natural gas were used as heat sources for cooking in homes but for little else.

As the technology for piping gas from the source began to improve, it became possible to pipe natural gas over thousands of miles. This has meant that natural gas has become as convenient as petroleum and **coal** to use as a fuel source, and often with far less pollution. Natural gas burns with almost no byproducts except for carbon dioxide and water (as opposed to coal which often has large amounts of sulfur in it), and the heat released from the reaction (combustion of any of the hydrocarbon components of natural gas is an exothermic process). The combustion of methane, the most prevalent component of natural gas, is described by the reaction below:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O + \text{heat energy}$$

Ethane is used less as a fuel source than as a starting material for the production of ethylene (acetylene), which is used in welding.

Both butane and propane are relatively easy to liquefy and store. Liquefied propane and butane are used in disposable lighters and as camping fuels.

Because gases take up large amounts of **space**, they can be inconvenient to transport and store. The ability to liquefy the components of natural gas (either as a mixture or in isolation) has made natural gas much more practical as an energy source. The liquefaction of natural gas takes advantage of the different boiling points of methane, ethane, and other gases as a way of purifying each substance. A combination of refrigeration and increased pressure allows the individual gases to be stored and transported conveniently. At one time, the natural gas that often accompanied petroleum in the ground was simply burned off as a means of getting rid of it. Recently, however, this gas has been collected, liquefied and used along with the petroleum.

See also Fuels and fuel chemistry; Petroleum extraction

NEPTUNE • *see* SOLAR SYSTEM

NESOSILICATES

The most abundant rock-forming **minerals** in the **crust** of the earth are the silicates. They are formed primarily of **silicon** and **oxygen**, together with various **metals**. The fundamental unit of these minerals is the silicon-oxygen tetrahedron. These tetrahedra have a pyramidal shape, with a relatively small, positively charged silicon cation (Si^{+4}) in the center and four larger, negatively charged oxygen anions (O^{-2}) at the corners, producing a net charge of –4. **Aluminum** cations (Al^{+3}) may substitute for silicon, and various anions such as hydroxyl (OH^{-}) or fluorine (F^{-}) may substitute for oxygen. In order to form stable minerals, the charges that exist between tetrahedra must be neutralized. This can be accomplished by the sharing of oxygen cations between tetrahedra, or by the binding together adjacent tetrahedra with various metal cations. This in turn creates characteristic silicate structures that can be used to classify silicate minerals into **cyclosilicates**, **inosilicates**, nesosilicates, **phyllosilicates**, **sorosilicates**, and **tectosilicates**.

The simplest silicates are the nesosilicates, formed by individual silicon-oxygen tetrahedra. There is some substitution of aluminum for silicon in the tetrahedra, but not as much as in other types of silicate minerals. The negatively charged, isolated tetrahedra in nesosilicates are held together by various metal cations. The garnet group of nesosilicates is commonly found in metamorphic rocks and more rarely in **igneous rocks**, and the metal cations that are typically found in garnet minerals include aluminum, calcium, chromium, magnesium, manganese, and **iron**. Garnet minerals include almandine ($Fe_3Al_2Si_3O_{12}$), grossularite ($Ca_3Al_2Si_3O_{12}$), and uvarovite ($Ca_3Cr_2Si_3O_{12}$). The minerals of the **olivine** group are nesosilicates commonly found in iron- and magnesium-rich igneous rocks. The chemical formula of olivine is given as $(Mg,Fe)_2SiO_4$, but a complete solid solution exists between the end-members forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). The nesosilicate mineral zircon ($ZrSiO_4$) commonly forms in igneous rocks, and is so chemically stable that it becomes a common accessory mineral in many sediments and **sedimentary rocks**.

See also Mineralogy

NEUTRONS • *see* ATOMIC THEORY

NEW MADRID EARTHQUAKE • *see* MID-PLATE EARTHQUAKES

NEWTON, SIR ISAAC (1642-1727)

English physicist

1n 1687, English physicist Sir Isaac Newton published a law of universal gravitation in his important and profoundly influential work *Philosophiae Naturalis Principia Mathematica (*Mathematical principles of natural philosophy*)*. Newton articulated a law of universal gravitation that states that bodies with mass attract each other with a force that varies directly as the product of their masses and inversely as the square of the distance between them. This mathematically elegant law, along with Newton's laws of motion, became the guiding models for the future development of physical law.

Newton admitted having no fundamental explanation for mechanism of gravity itself. In *Principia* Newton stated, "I have been unable to discover the cause of those properties of gravity from phenomena, and I feign no hypotheses" (regarding its mechanism). Moreover, Newton asserted, "To us it is enough that gravity does really exist, and act according to the laws which we have explained, and abundantly serves to account for the motions of the celestial bodies and our seas." Newton's law of gravitation proved to be a precise and effective tool. A truly universal law, it could be verified by the simplest fall of an apple or measured against the most detailed observations of celestial movements. Ultimately, Newton's law of universal gravitation would provide, in the twentieth century, evidence of the existence of black holes. The Newtonian methodology of simplifying mass to a point mass (i.e., with regard to gravitational fields, all of the mass of a body can be considered to lie in a center of mass without physical **space**) also proved a brilliant simplification that enabled the mathematical advancement of mechanics and electromagnetism.

Because Newton's law of universal gravitation was so mathematically simple and precise it strengthened the idea that all the laws describing the universe should be mathematical.

Born in Woolsthorpe, Lincolnshire, England, Newton was a premature baby who was not expected to live. His father had died three months before the birth, and his mother remarried three years later, leaving Newton in the care of his grandparents. Newton did not distinguish himself in school, and his mother removed him in the late 1650s to work on the family farm, but Newton proved a worse farmer than scholar. His uncle, however, encouraged the boy to go to Cambridge in 1660. Five years later Newton graduated, even though he had failed a scholarship exam in 1663 due to his lack of knowledge concerning geometry.

Newton returned to the farm shortly thereafter to escape the Bubonic plague, which at the time was decimating London. While at the farm in 1666, Newton first developed his law of universal gravitation. When Newton made calculations of what the rate of fall for the **Moon** should be, he came up short of what was actually observed and was quite disappointed. The problem was twofold; first, the radius of the earth was not known with precision and the size Newton used was too small. Second, he was not absolutely certain he was correct in making his calculations based on the gravitational force at the center of Earth, as opposed to the surface. Because of these issues, he set aside his work on gravity for 15 years.

During this same time, Newton began to experiment with light. Newton passed a beam of sunlight through a prism of **glass** and observed it was refracted into a spectrum. He passed the spectrum through a second prism, and the light was recombined into a white spot. In 1672, Newton was elected to the Royal Society.

During his life Newton became involved in often bitter disputes with other scholars, especially his dispute with German mathematician Gottfried Wilhelm von Leibniz (1646–1716) over credit for the development of calculus. Although the notations and nomenclature used in modern calculus most directly trace back to the work of Leibniz, Newton has received the most credit for the development of the calculus in textbooks. Modern historians of science generally conclude that the feud between Newton and Leibniz was essentially groundless. A modern analysis of the notes of Newton and Leibniz clearly established that Newton secretly developed calculus some years before Leibniz published his version but that Leibniz independently developed the calculus so often credited exclusively to Newton.

Newton died on March 20, 1727, at the age of 84, and his vast influence upon science continued, later rivaled only by that of Charles Darwin and **Albert Einstein**.

See also Gravitational constant; Gravity and the gravitational field; Relativity theory

NICHE

In geophysical and ecological terms, a niche designates the relationship between a species and its **area** of inhabitation. The term is specifically used to describe a species' unique position both in terms of physical area, and as a set of characteristics that relate the species' biological and ecological functions to its geophysical environment.

Although not the subject of this article, the term niche is also used to describe a type of glacier (e.g., niche glacier) that forms inside an irregular recess on or within a mountainside.

Four distinct stages of niche theory development in biological ecology can be identified: (1) Joseph Grinnell's original formulation of niche (in 1917 and 1928) as a geophysical spatial unit; (2) Charles Elton's formulation (in 1927) of niche as a functional unit; (3) Gause's (1934) competitive exclusion principle; and (4) E. Evelyn Hutchinson's concept of multidimensional niche in the 1950s.

Although Darwin understood the idea of niche and a few other biologists used the term earlier, Grinnell is credited with its formal development. To Grinnell, niche was a spatial unit that stood for the "concept of the ultimate distributional unit, within which each species is held by its structural and instinctive limitations." His conception of niche was "preinteractive"—that is, it referred to the entire area within which an organism could survive in the absence of other organisms. This is in contrast to the "post-interactive" niche, the actual place occupied by the organism in an environment after it has interacted with other organisms.

At about the same time, Charles Elton was developing the niche concept along somewhat different lines. Elton conceived of niche as a functional unit to describe the organism's "place in the biotic environment, relations to food and enemies." Although Elton presented niche as an organism's ecological position in a larger framework like a community or ecosystem, he then restricted its use to the food habits of an organism. Accordingly, Elton's niche is considered to be postinteractive.

Gause is credited with being the first investigator to perceive the connection between natural selection, competition, and niche and to see the interacting aspects of these concepts. Gause stated that "it is admitted that, as a result of competition, two similar species scarcely ever occupy similar niches, but displace each other in such a manner that each takes possession of certain peculiar kinds of food and modes of life in which it has an advantage over its competitor. Gause experimentally tested the general conclusions drawn from the Lotka-Volterra competitive equations, confirming and amplifying them. These conclusions are summarized in the "competitive exclusion principle," which states that two species cannot coexist at the same locality if they have identical ecological requirements. Gause based the principle on an Eltonian definition of niche.

The Eltonian niche dominated ecological theory during the period 1930–1950 and began to be referred to as an organism's "occupation" or "profession." Hutchinson responded to this rather limited idea of niche by incorporating selected features from both Grinnell's and Elton's niche definitions and redefining niche as an "n-dimensional hypervolume," an abstract multidimensional **space** defining the environmental limits within which an organism is able to survive and reproduce. Hutchinson's "fundamental niche" is preinteractive, composed of "close to innumerable" dimensions, each corresponding to some requisite for a species. By setting the number of defining dimensions at "close to innumerable," Hutchinson attempted to illustrate the complexity of the systems within which organisms exist and interact. He depicted it by plotting each identifiably important environmental variable along an axis to show the points below which and above which the given organism could not survive.

Hutchinson's "realized niche" usually corresponds to a smaller hypervolume because competition and other interactions serve to restrict organisms from some parts of their fundamental or potential niche. Although most current works in niche theory use some variation of Hutchinson's multidimensional niche, both the Eltonian and the Hutchinson niches are still found in contemporary ecology and are still useful. Any application of niche, however, is only an approximation of reality, because niche dimensions are too numerous to be counted.

See also Archeological mapping; Physical geography; Topography and topographic maps

NIMBOSTRATUS CLOUD • *see* CLOUDS AND CLOUD TYPES

NORTH AMERICA

The landmass occupied by the present-day countries of Canada, the United States, and the Republic of Mexico make up North America. Greenland (Kalaallit Nunaat), an island landmass to the northeast of Canada, is also included in North America, for it has been attached to Canada for almost two billion years.

Plate tectonics is the main force of nature responsible for the geologic history of North America. Over time, the plates have come together to form the continents, including North America. Other processes, such as **sedimentation** and **erosion**, modify the shape of the land that has been forged by plate tectonics.

North American geologic history includes several types of mountain ranges as a result of plate tectonics. When the edge of a plate of Earth's **crust** runs over another plate, forcing the lower plate deep into Earth's elastic interior, a long, curved mountain chain of volcanoes usually forms on the forward-moving edge of the upper plate. When this border between two plates forms in the middle of the ocean, the volcanic mountains form a string of islands, or archipelago, such as the Antilles and the Aleutians. This phenomenon is called an island arc.

When the upper plate is carrying a continent on its forward edge, a mountain chain, like the Cascades, forms right on the forward edge. This edge, heavily populated with volcanoes, is called a continental arc. The volcanic mountains on the plate border described above can run into a continent, shatter the collision **area** and stack up the pieces into a mountain range. This is how the Appalachians were formed.

When a continent-sized "layer cake" of **rock** is pushed, the upper layers move more readily than the lower layers. The layers separate from each other, and the upper few miles of rock move on ahead, floating on fluid pressure between the upper and lower sections of the crust like a fully loaded tractor trailer gliding effortlessly along an icy road. The flat surface where moving layers of crust slide along the top of the layers beneath it is called a thrust fault, and the mountains that are heaved up where the thrust fault reaches the surface are one kind of fault block mountains. The mountains of Glacier National Park slid along the Lewis thrust fault over younger rocks, and out onto the Great Plains.

Mountain ranges start being torn down by physical and chemical forces while they are still rising. North America has been criss-crossed by one immense range of mountains after another throughout its almost four-billion-year history.

A range of mountains may persist for hundreds of millions of years, like the Appalachians. On repeated occasions, the warped, folded rocks of the Appalachians were brought up out of the continent's basement and raised thousands of feet by tectonic forces. If mountains are not continuously uplifted, they are worn down by erosion in a few million years. In North America's geologic past, eroded particles from its mountains were carried by streams and dumped into the continent's inland **seas**, some of which were as large as the present-day Mediterranean. Those **rivers** and seas are gone from the continent, but the sediments that filled them remain, like dirt in a bathtub when the **water** is drained. The roots of all the mountain ranges that have ever stood in North America all still exist, and much of the **sand** and **clay** into which the mountains were transformed still exists also, as rock or **soil** formations.

Various parts of North America were formed all over the world, at various times over four billion years, and were brought together and assembled into one continent by the endless process of plate tectonics. What is now called North America began to form in the first two and one-half billion years of Earth's history, a period of time called the **Archean** Eon.

Some geologists speculate that the earth that created the oldest parts of North America barely resembled the middle-aged planet on which we live. The planet of four billion years ago had cooled enough to have a solid crust, and **oceans** of liquid water. But the crust may have included hundreds of small tectonic plates, moving perhaps 10 times faster than plates move today. These small plates, carrying what are now the most ancient rocks, scudded across the oceans of a frantic crazy-quilt planet. Active volcanoes and rifts played a role in rock formation on the Archean Earth. The oldest regions in North America were formed in this hyperactive world. These regions are in Greenland, Labrador, Minnesota, and Wyoming.

In the late Archean Eon, the plates of Earth's crust may have moved at a relatively high speed. Evidence of these wild times can be found in the ancient core of North America. The scars of tectonic events appear as rock outcrops throughout the part of northern North America called the Canadian Shield. One example of this kind of scar, a **greenstone belt**, may be the mangled remains of ancient **island arcs** or rifts within continents. Gold and chromium are found in the greenstone belts, and deposits of copper, zinc, and nickel. Formations of **iron** ore also began to form in the Archean Eon, and **fossils** of microscopic cyanobacteria-the first life on Earth—are found imbedded in them.

North America's little Archean continents slammed together in a series of mountain-building collisions. The core of the modern continent was formed 1,850 million years ago when five of these collisions occurred at once around northeastern Canada. This unified piece of ancient continental crust, called a **craton**, lies exposed at the surface in the Canadian Shield, and forms a solid foundation under much of the rest of the continent.

In the two billion years of the Proterozoic Eon (2,500–570 million years ago), North America's geologic setting became more like the world as we know it. The cores of the modern continents were assembled, and the first collections of continents, or **supercontinents**, appeared. Life, however, was limited to bacteria and algae, and unbreatheable gases filled the atmosphere. Rampant erosion filled the rivers with mud and sand, because no land plants protected Earth's barren surface from the action of rain, **wind**, heat, and cold.

Rich accumulations of both rare and common metallic elements make Proterozoic rocks a significant source of mineral wealth for North America, as on other continents. Chromium, nickel, copper, tin, titanium, vanadium, and platinum ores are found together in the onion-like layers of crystallized **igneous rocks** called layered intrusions. Greenstone belts are mined for copper, **lead**, and zinc, each of which is mixed with sulfur to form a sulfide mineral. Sulfide **minerals** of lead and zinc are found in limestones formed in shallow seas, while mines in the ancient continental river and **delta** sediments uncover buried vanadium, copper, and uranium ores.

During the middle to late Proterozoic Eon, continental collisions attached new pieces of continental crust to North America's southern, eastern, and western borders. Between 30% and 40% of North America joined the continent in the Proterozoic. The crust underlying the continental United States east of Nevada joined the craton, as well as the crust underlying the Sierra Madre Occidental of Sonora, Chihuahua, and Durango in Mexico. The Mazatzal Mountains, whose root outcrop is in the Grand Canyon's inner gorge, rose in these mountain-building times in southern and central North America.

North America experienced the sea washing over its boundaries many times during the three-billion-plus years of its Archean and Proterozoic history. Life had flourished in the shallow tidewater. Algae, a long-term resident of North America, was joined later by worms and other soft-bodied animals. Little is known of early soft-bodied organisms, because they left no skeletons to become fossils. Only a handful of good fossils remain from the entire world's immense **Precambrian** rock record.

Then, about 570 million years ago, several unrelated lineages of shell-bearing sea animals appeared. This was the beginning of the **Phanerozoic Eon** of earth history, which has lasted from 570 million years ago to the present day. Vast seas covered much of North America in the early Phanerozoic, their shorelines changing from one million-year interval to the next. The seas teemed with creatures whose bones and shells we have come to know in the **fossil record**. These oceanic events are memorialized in the layers of stone each sea left behind, lying flat in the continent's heartland, and folded and broken in the cordilleras. Geologists have surveyed the stacked sheets of stone left by ancient North American seas and have made maps of the deposits of each continental sea. The stacked layers are divided into sequences, each named for the sea that laid it down. Each sequence consisted of a slow and complex flooding of the continent. Sea level mountain uplift, the growth of deltas, and other factors continually changed the shape of the continental sea.

The eastern coast of North America was once part of an ancient "Ring of Fire" surrounding an ocean that has disappeared forever from Earth. From Greenland to Georgia, and through the Gulf Coast states into Mexico, the collision of continents raised mountains comparable to the Himalayas and Alps of today. Several ranges were raised up on the eastern border of North America between 480 and 230 million years ago.

Another collision about 450 million years ago created the Acadian mountain range, whose roots are exposed today in Newfoundland. These mountains began to be torn down by rain and wind, and by the time they had worn down to nothing, more than 63,000 cubic miles of sediment made from them had been dumped into the shallow continental sea between New York and Virginia—about the same amount of rock as the Sierra Nevadas of today. The bones of amphibians, the first land animals, are found in the rocks laid down by the streams of East Greenland.

The sleepless crust under North America's Pennsylvanian-age borders tossed and turned in complex ways. Three hundred million years ago, North America sat on the equator, its vast inland sea surrounded by rain **forests** whose fossilized remains are the **coal** deposits of the eastern United States. Small mountain ranges rose out of the sea that covered the center of the continent in Colorado, Oklahoma, and Texas. The Ouachitas stood in the Gulf Coast states, the last great mountain range to stand there. In the eastern United States, the Allegheny Mountain Range stood where the Acadian and Taconic Ranges had stood before.

The Ouachitas welded **South America** to the Gulf coast, at roughly the same time as the Alleghenies welded the East coast of North America to West **Africa**. The Ouachitas and Alleghenies stretched, unbroken, all the way around the eastern and southern coasts of North America. This joining of the world's continents formed Pangaea, the most recent supercontinent in geologic history. Pangaea's 150 million year history ended with the birth of the Atlantic Ocean and the separation of North and South America. As South America and Africa tore away from North America, Florida was left behind, attached to the intersection of the Allegheny and Ouachita Mountains. Another legacy of this cracking of Earth's crust is the New Madrid Fault, which runs through the North American Plate under the Mississippi Valley.

Around 340 million years ago, an offshore island arc, called the Antler Arc, struck the shores about where Nevada and Idaho now are (then the westernmost part of the continent), extending the shoreline of North America a hundred miles westward.

By 245 million years ago, the beginning of the age of dinosaurs, another island arc had run into the American West. The Golconda Arc added a Sumatra-sized piece of land to North America, and the continent bulged out to present-day northern California.

After the Golconda Arc piled onto the West Coast of that time, the crust broke beneath the continent's border, and the ocean's plate ran under North America's west coast. A continental arc was born around 230 million years ago in western North America, and its volcanoes have been erupting frequently from the dawn of the age of dinosaurs (the **Mesozoic Era**) until today.

Several more island arcs struck western North America since the middle **Jurassic Period**. The **granite** mountains of the Sierra Nevada are the roots of one of these island arcs. Landmasses created on the Pacific Plate have been scraped from it. This mechanism is the origin of the West Coast's ranges, the Cascades, and much of British Columbia and Alaska's southern coast.

A range of fault block mountains rose far inland as the continent was squeezed from west to east. The Sevier Mountains stood west of the Cretaceous Period's interior seaway, in what is now Montana, Idaho, Nevada, and Utah. The dinosaurs of that time (80–130 million years ago) left their tracks and remains in the mud and sand worn off these mountains.

In the same manner as large island chains were carried to North America on moving plates of oceanic crust, small pieces of land came to the coasts in this way as well. Numerous "exotic terrains," impacting on the western coasts during the Mesozoic and Cenozoic Eras, added large areas now covered by British Columbia, Washington, Oregon, California, and Mexico. These little rafts of continental crust were formed far from their present location, for the fossils in them are of creatures that lived halfway around the world—but never in North America. A sizeable piece of continental crust—southern Mexico as far south as the Isthmus of Tehuantepec—joined northern Mexico between 180–140 million years ago.

Starting 80 million years ago, new forces began to act on the inland west. Geologists do not know exactly what happened beneath the crust to cause these changes, but the features created on the surface by tectonic action underneath the crust are well known.

At the same time as the Sevier Mountains ceased to rise, a similar range, facing the opposite direction, began to move upward. Earth's upper crust beneath the Rocky Mountain states was shoved westward as the Laramides were forming, lifting the Rocky Mountains for the first time. These first modern Rocky Mountains drained the continent's last great shallow sea of inland North America as they rose. Huge mountains now stood in places where seas had rolled over Colorado, Wyoming, Utah, Idaho, Montana, and Alberta. In Mexico, the Laramides raised the Sierra Madre Occidental, and formed the mineral deposits that enrich Sonora, Chihuahua, Durango, and Zacatecas. In Colorado, Wyoming, and neighboring states, the Rocky Mountains began to erode away, and by 55 million years ago, the first Rockies had disappeared from the surface—the mountains' roots were buried in sediment from the eroded mountaintops. More recent uplift again exposed the Rockies, and Ice Age **glaciers** sculpted their tops into today's sharp peaks.

Twenty-five million years ago, after a quiet interlude, North America's western continental arc awoke, and its abundant volcanoes again added new rock to the continent from British Columbia to Texas and down the mountainous spine of Mexico. The only area in the Southwest in which volcanoes were uncommon was the Colorado Plateau, whose immunity to the tectonic forces around it is still a mystery. Around the borders of the Colorado Plateau's remarkably thick crust, one volcanic catastrophe after another covered the land. In this time, the San Juan Mountains were formed in Colorado. The Rocky Mountains began to slide westward and rose again on the thrust faults beneath them.

Ten million years ago, the Great Basin area of the United States was much shorter when measured east to west than it is today. It was then a mountainous highland. Some geologists propose that Nevada was an alpine plateau like Tibet is today—perhaps more than 10,000 ft (3,048 m) high. Starting then and continuing for five million years, this area began to be pulled apart. Long faults opened in the crust, and mountain-sized wedges slowly fell between ridges that were still standing on the unbroken basement rock miles below. Sediment from the erosion of these new ridges filled the valleys, enabling the valleys to become reservoirs of underground water, or aquifers. The low parts got so low that the area is indeed a basin; water does not flow out of it. Some geologists believe that the Basin and Range province stretches around the Colorado Plateau, into Texas, and extends down the Sierra Madre Occidental as far south as Oaxaca.

Another kind of pulling-apart of the continent happened in New Mexico's Rio Grande Rift. As at the Keewenaw Rift a billion years before, tectonic forces from beneath Earth's crust began pulling the surface apart just as east Africa is being pulled apart today. The broad rift's mountainous walls eroded, and the sediment from that erosion piled up in the ever-widening valley. A new ocean was about to be formed in the southwest. **Lava** poured from fissures in the crust near Taos, New Mexico, filling the valley floor. Also like the Keewenaw Rift, the Rio Grande Rift stopped growing after a few million years, as the tectonic processes ceased pulling the continent apart. The modern Rio Grande was born as a consequence of this rift, and still runs through the rift valley.

A cataclysmic volcanic event happened in Oregon and Washington 17 million years ago. For an unknown reason, perhaps a disturbance deep in Earth's mantle, or a meteor impact, lava began pouring out of cracks in Earth. So much lava poured onto the surface at once that it ran from southeastern Oregon down the Columbia River valley to the Pacific Ocean. Huge cracks in the ground called fissures flooded broad areas with **basalt** lava over about 500,000 years. This flood of basalt is called the Columbia River Plateau. A hot spot, or an upwelling of molten rock from Earth's mantle, appears to have caused the Columbia River Plateau. As the North American Plate moved westward between then and now, the hot spot stayed in one place, scorching holes in Earth's crust under Idaho and erupting the lava that makes the Snake River Plain a fertile farmland. This hot spot is assumed to be the heat source that powers the geysers of Yellowstone National Park.

In the early Jurassic Period, 200 million years ago, the northernmost edge of North America tore away from the continent and began rotating counterclockwise. This part of the continent came to rest to the northwest of North America, forming the original piece of Alaska—its northernmost mountains, the Brooks Range. In the late **Cretaceous Period**, the farthest part of this landmass from North America struck the edge of Siberia, and became the Chukotsk Peninsula. The remaining landmass of Alaska joined North America bit by bit, in the form of exotic terrains. The Aleutians, a classic island arc, formed in the **Tertiary Period**. The about 40 active volcanoes of the Aleutians have erupted numerous times in the twentieth century, including several eruptions in the last decade from Mt. Augustine, Pavlov, Shishaldin, and Mt. Redoubt.

National Bison Range, Montana. © *Annie Griffiths Belt/Corbis. Reproduced by permission.*

For reasons that are not yet fully understood, Earth periodically enters a time of planet-wide cooling. Large areas of the land and seas are covered in ice sheets thousands of feet thick, which remain unmelted for thousands or hundreds of thousands of years. Today, only Greenland and **Antarctica** lie beneath continent-sized glaciers. But in the very recent geologic past, North America's northern regions, including the entire landmass of Canada, were ground and polished by an oceanic amount of water frozen into a single mass of ice. This ice began to accumulate as the planet's **weather** cooled, and began to stay frozen all year round. As it built up higher and higher, it began to move out from the piled-high center, flowing while still solid.

Vast amounts of Canadian soil and rock, called glacial **till**, rode on the ice sheets as they moved, or surfed slowly before the front of the ice wall. Some of the richest farmland in the United States Midwest and northeast arrived in its present location in this way-as well as boulders that must be removed from fields before plowing. In the unusual geographic conditions following the retreat of the ice sheets, barren soil lay on the landscape, no longer held down by the glacier. Windstorms moved tremendous amounts of this soil far from where the glacier left it, to settle out of the sky as a layer of fertile soil, called loess in German and English. Loess soils settled in the Mississippi and Missouri Valleys, and also Washington, Oregon, Oklahoma, and Texas.

This continental **glaciation** happened seven times over the last 2.2 million years. Warm intervals, some of them hundreds of thousands of years long, stretched between these planetary deep-freezes. Geologists do not agree whether the ice will return or not. Even if the present day is in a warm period between glaciations, tens or hundreds of thousands of years may elapse before the next advance of the ice sheets.

California lies between two different kinds of plate boundaries. To the south, the crust under California is growing; to the north it is shrinking. The part of California that sits on the Pacific Plate between these two forces is moved northward in sudden increments of a few feet which are felt as earthquakes. A few feet at a time, in earthquakes that happen every few decades, the part of California west of the San Andreas Fault will move northward along the coast.

Active faults also exist elsewhere in the United States, in the Midwest and in South Carolina. The last sizeable earthquakes in these regions occurred more than a hundred years ago, and geologists assume that earthquakes will probably occur within the next hundred years. The Pacific Northwest and Alaska, sitting atop active tectonic environments, will certainly be shaken by earthquakes for millions of years to come.

The Great Basin, the western Rocky Mountains, and the United States northeast are all considered tectonically active enough for earthquakes to be considered possible.

North America's volcanic mountain ranges, the Cascades, and the relatively recent Mexican Volcanic Belt, have erupted often in the recent geologic past. These mountains will certainly continue to erupt in the near geologic future.

See also Continental drift theory; Continental shelf; Earth (planet); Faults and fractures; Fossils and fossilization; Ice ages; Orogeny

NORTH POLE • *see* GEOGRAPHIC AND MAGNETIC POLES

NORTHERN LIGHTS • *see* AURORA BOREALIS AND AURORA AUSTRALIALIS

NUCLEAR FISSION

Nuclear fission is a process in which the nucleus of an **atom** splits, usually into two daughter nuclei. Spontaneous fission of uranium and other elements in Earth's interior provides an internal source of heat that drives **plate tectonics**. Fission tracks in mineral **crystals**, a result of spontaneous fission of uranium, can be used in radiometric dating of **rock** and rock layers.

Long before the internal construction of the atom was well understood in terms of protons, neutrons, and electrons, nuclear transformations that resulted in observable **radioactivity** were observed as early as 1896 by French physicist Henri Becquerel (1852–1908). In 1905, British physicist Ernst Rutherford (1871–1937) and American physicist Bertram Borden Boltwood (1870–1927) first used radioactive decay measurements to date **minerals**.

The fission reaction was discovered when a target of uranium was bombarded by neutrons. Fission fragments were shown to fly apart with a large release of energy. The fission reaction was the basis of the atomic bomb first developed by the United States during World War II. After the war, controlled energy release from fission was applied to the development of nuclear reactors. Reactors are utilized for production of **electricity** at nuclear power plants, for propulsion of ships and submarines, and for the creation of radioactive isotopes used in medicine and industry.

The fission reaction was first articulated by two German scientists, Otto Hahn (1879–1968) and Fritz Strassmann (1902–1980). In 1938, Hahn and Strassmann conducted a series of experiments in which they used neutrons to bombard various elements. Bombardment of copper, for example, produced a radioactive form of copper. Other elements became radioactive in the same way. When uranium was bombarded with neutrons, however, an entirely different reaction occurred. The uranium nucleus apparently underwent a major disruption. Accordingly, the initial evidence for the fission process came from chemical analysis. Hahn and Strassmann published a scientific paper showing that small amounts of barium (element 56) were produced when uranium (element 92) was bombarded with neutrons. Hahn and Strassmann questioned how a single neutron could transform element 92 into element 56.

Lise Meitner (1878–1968), a long-time colleague of Hahn who had left Germany due to Nazi persecution, suggested a helpful model for such a reaction. One can visualize the uranium nucleus to be like a liquid drop containing protons and neutrons. When an extra neutron enters, the drop begins to vibrate. If the vibration is violent enough, the drop can break into two pieces. Meitner named this process "fission" because it is similar to the process of cell division in biology. Moreover, it takes only a relatively small amount of energy to initiate nuclear instability.

Scientists in the United States and elsewhere quickly confirmed the idea of uranium fission, using other experimental procedures. For example, a cloud chamber is a device in which vapor trails of moving nuclear particles can be seen and photographed. In one experiment, a thin sheet of uranium was placed inside a cloud chamber. When it was irradiated by neutrons, photographs showed a pair of tracks going in opposite directions from a common starting point in the uranium. Clearly, a nucleus had been photographed in the act of fission.

Another experimental procedure used a Geiger counter, which is a small, cylindrical tube that produces electrical pulses when a radioactive particle passes through it. For this experiment, the inside of a modified Geiger tube was lined with a thin layer of uranium. When a neutron source was brought near it, large voltage pulses were observed, much larger than from ordinary radioactivity. When the neutron source was taken away, the large pulses stopped. A Geiger tube without the uranium lining did not generate large pulses. Evidently, the large pulses were due to uranium fission fragments. The size of the pulses showed that the fragments had a very large amount of energy.

To understand the high energy released in uranium fission, scientists made some theoretical calculations based on German-American physicist Albert Einstein's (1879–1955) famous equation $E=mc^2$. The Einstein equation states that mass (m) can be converted into energy (E) (and, conversely that energy can create mass). The conversion factor becomes c, the velocity of light squared. One can calculate that the total mass of the fission products remaining at the end of the reaction is slightly less than the mass of the uranium atom plus neutron at the start. This decrease of mass, multiplied by c, shows numerically why the fission fragments are so energetic.

Through fission, neutrons of low energy can trigger off a very large energy release. With the imminent threat of war in l939, a number of scientists began to consider the possibility that a new and very powerful "atomic bomb" could be built from uranium. Also, they speculated that uranium perhaps could be harnessed to replace **coal** or oil as a fuel for industrial power plants.

Nuclear reactions in general are much more powerful than chemical reactions. A chemical change such as burning coal or even exploding TNT affects only the outer electrons of an atom. A nuclear process, on the other hand, causes changes among the protons and neutrons inside the nucleus. The energy of attraction between protons and neutrons is about a million times greater than the chemical binding energy between atoms. Therefore, a single fission bomb, using nuclear energy, might destroy a whole city. Alternatively, nuclear electric power plants theoretically could run for a whole year on just a few tons of fuel.

In order to release a substantial amount of energy, many millions of uranium nuclei must split apart. The fission process itself provides a mechanism for creating a so-called chain reaction. In addition to the two main fragments, each fission event produces two or three extra neutrons. Some of these can enter nearby uranium nuclei and cause them in turn to fission, releasing more neutrons, which causes more fission, and so forth. In a bomb explosion, neutrons have to increase very rapidly, in a fraction of a second. In a controlled reactor, however, the neutron population has to be kept in a steady state. Excess neutrons must be removed by some type of absorber material (e.g., neutron absorbing control rods).

In l942, the first nuclear reactor with a self-sustaining chain reaction was built in the United States. The principal designer was Enrico Fermi (1901–1954), an Italian physicist and the l938 Nobel Prize winner in physics. Fermi emigrated to the United States to escape from Benito Mussolini's fascism. Fermi's reactor design had three main components: lumps of uranium (the fuel), blocks of **carbon** (the moderator, which slows down the neutrons), and control rods made of cadmium (an excellent neutron absorber). Fermi and other scientists constructed the first nuclear reactor pile at the University of Chicago. When the pile of uranium and carbon blocks was about 10 ft (3 m) high and the cadmium control rods were pulled out far enough, Geiger counters showed that a steady-state chain reaction had been successfully accomplished. The power output was only about 200 watts, but it was enough to verify the basic principle of reactor operation. The power level of the chain reaction could be varied by moving the control rods in or out.

General Leslie R. Groves was put in charge of the project to convert the chain reaction experiment into a usable military weapon. Three major laboratories were built under wartime conditions of urgency and secrecy. Oak Ridge, Tennessee, became the site for purifying and separating uranium into bomb-grade material. At Hanford, Washington, four large reactors were built to produce another possible bomb material, plutonium. At Los Alamos, New Mexico, the actual work of bomb design was started in l943 under the leadership of the physicist J. Robert Oppenheimer (1904–1967).

The fissionable uranium isotope, uranium-235, constitutes only about l% of natural uranium, while the non-fissionable neutron absorber, uranium-238, makes up the other 99%. To produce bomb-grade, fissionable uranium-235, it was necessary to build a large isotope separation facility. Since the plant would require much electricity, the site was chosen to be in the region of the Tennessee Valley Authority (TVA). The technology of large-scale isotope separation involved solving many difficult, unprecedented problems. By early l945, the Oak Ridge Laboratory was able to produce kilogram amounts of uranium-235 purified to better than 95%.

An alternate possible fuel for a fission bomb is plutonium-239. Plutonium does not exist in nature but results from radioactive decay of uranium-239. Fermi's chain reaction experiment had shown that uranium-239 could be made in a reactor. However, to produce several hundred kilograms of plutonium required a large increase from the power level of Fermi's original experiment. Plutonium production reactors were constructed at Hanford, Washington, located near the Columbia river to provide needed cooling **water**. A difficult technical problem was how to separate plutonium from the highly radioactive fuel rods after irradiation. This was accomplished by means of remote handling apparatus that was manipulated by technicians working behind thick protective **glass** windows.

With uranium-235 separation started at Oak Ridge and plutonium-239 production under way at Hanford, a third laboratory was set up at Los Alamos, New Mexico, to work on bomb design. In order to create an explosion, many nuclei would have to fission almost simultaneously. The key concept was to bring together several pieces of fissionable material into a so-called critical mass. In one design, two pieces of uranium-235 were shot toward each other from opposite ends of a cylindrical tube. A second design used a spherical shell of plutonium-239, to be detonated by an "implosion" toward the center of the sphere.

The first atomic bomb was tested at an isolated **desert** location in New Mexico on July l6, l945. President Truman then issued an ultimatum to Japan that a powerful new weapon could soon be used against them. On August 8, a single atomic bomb destroyed the city of Hiroshima with over 80,000 casualties. On August 11, a second bomb was dropped on Nagasaki with a similar result. Japan surrendered three days later to end WWII.

The decision to use the atomic bomb has been vigorously debated over the years. It ended the war and avoided many casualties that a land invasion of Japan would have cost. However, the civilians who were killed by the bomb and the survivors who developed radiation sickness left an unforgettable legacy of fear. The horror of mass annihilation in a nuclear war is made vivid by the images of destruction at Hiroshima. The possibility of a ruthless dictator or a terrorist group obtaining nuclear weapons is a continuing threat to world peace. In late 2001, in the aftermath of the terrorist attacks on the World Trade Center in New York, evidence became public of terrorist attempts to acquire weapons-grade uranium and the other technology related to bomb production.

The first nuclear reactor designed for producing electricity was put into operation in 1957 at Shippingsport, Pennsylvania. From l960 to l990, more than 100 nuclear power plants were built in the United States. These plants now generate about 20% of the nation's electric power. Worldwide, there are over 400 nuclear power stations.

The most common reactor type is the pressurized water reactor (abbreviated PWR). The system operates like a coal-burning power plant, except that the firebox of the coal plant is replaced by a reactor. Nuclear energy from uranium is released in the two fission fragments. The fuel rod becomes very hot because of the cumulative energy of fissioning nuclei. A typical reactor core contains hundreds of these fuel rods.

The immense destructive power of the atom unleased in the atomic bomb, forming its distinctive mushroom-shaped cloud. © *UPI/Corbis-Bettmann. Reproduced by permission.*

Water is circulated through the core to remove the heat. The hot water is prevented from boiling by keeping the system under pressure (i.e., creating superheated steam).

The pressurized hot water goes to a heat exchanger where steam is produced. The steam then goes to a turbine, which has a series of fan blades that rotate rapidly when hit by the steam. The turbine is connected to the rotor of an electric generator. Its output goes to cross-country transmission lines that supply the electrical users in the region with electricity. The steam that made the turbine rotate is condensed back into water and is recycled to the heat exchanger.

Safety features at a nuclear power plant include automatic shutdown of the fission process by insertion of control rods, emergency water-cooling for the core in case of pipeline breakage, and a concrete containment shell. It is impossible for a reactor to have a nuclear explosion because the fuel enrichment in a reactor is intentionally limited to about 3% uranium-235, while almost l00% pure uranium-235 is required for a bomb. Regardless, nuclear power plants remain potential targets for terrorists who would seek to cause massive and lethal release of radioactivity by compromising the containment shell.

The fuel in the reactor core consists of several tons of uranium. As the reactor is operated, the uranium content gradually decreases because of fission, and the radioactive waste products (the fission fragments) build up. After about a year of operation, the reactor must be shut down for refueling. The old fuel rods are pulled out and replaced. These fuel rods, which are very radioactive, are stored under water at the power plant site. After five to 10 years, much of their radioactivity has decayed. Only those materials with a long radioactive lifetime remain, and eventually they will be stored in a suitable underground depository.

There are vehement arguments for and against nuclear power. As with other forms of producing electricity, nuclear power generation can have serious and unintended environmental impacts. The main objections to nuclear power plants are the fear of possible accidents, the unresolved problem of nuclear waste storage, and the possibility of plutonium diversion for weapons production by a terrorist group. The issue of waste storage becomes particularly emotional because leakage from a waste depository could contaminate ground water. Opponents of nuclear power often cite accidents at the Three Mile Island nuclear power plant in the United States and the massive leak at the Chernobyl nuclear plant in the USSR (now the Ukraine) as evidence that engineering or technical failures can have long lasting and devastating environmental and public health consequences.

The main advantage of nuclear power plants is that they do not cause **atmospheric pollution**. No smokestacks are needed because nothing is being burned. France initiated a large-scale nuclear program after the Arab oil embargo in l973 and has been able to reduce its **acid rain** and **carbon dioxide** emissions by more than 40%. Nuclear power plants do not contribute to **global warming**. Shipments of fuel are minimal so the hazards of coal transportation and oil spills are avoided.

Environmentalists remain divided in their opinions of nuclear power. It is widely viewed as a hazardous technology but there is growing concern about atmospheric pollution and dwindling fossil fuel reserves that may make increased usage of nuclear power more widespread.

See also Atom; Atomic mass and weight; Atomic number; Atomic theory; Chemical elements; Chemistry; Dating methods; Energy transformations; Radioactive waste storage (geological considerations); Radioactivity

NUCLEAR FUSION

Nuclear fusion is the process by which two light atomic nuclei combine to form one heavier atomic nucleus. As an example, a proton (the nucleus of a hydrogen **atom**) and a neutron will, under the proper circumstances, combine to form a deuteron (the nucleus of an atom of "heavy" hydrogen). In general, the mass of the heavier product nucleus is less than the total mass of the two lighter nuclei. Nuclear fusion is the initial driving process for the process of nucelosynthesis.

When a proton and neutron combine, the mass of the resulting deuteron is 0.00239 **atomic mass** units (amu) less than the total mass of the proton and neutron combined. This "loss" of mass is expressed in the form of 2.23 MeV (million electron volts) of kinetic energy of the deuteron and other particles and as other forms of energy produced during the reaction. Nuclear fusion reactions are like **nuclear fission** reactions, therefore, in that some quantity of mass is transformed into energy. This is the reason stars "shine" (i.e., radiate tremendous amounts of electromagnetic energy into **space**).

The particles most commonly involved in nuclear fusion reactions include the proton, neutron, deuteron, a triton (a proton combined with two neutrons), a helium-3 nucleus (two protons combined with a neutron), and a helium-4 nucleus (two protons combined with two neutrons). Except for the neutron, all of these particles carry at least one positive electrical charge. That means that fusion reactions always require very large amounts of energy in order to overcome the force of repulsion between two like-charged particles. For example, in order to fuse two protons with each other, enough energy must be provided to overcome the force of repulsion between the two positively charged particles.

As early as the 1930s, a number of physicists considered the possibility that nuclear fusion reactions might be the mechanism by which energy is generated in the stars. No familiar type of chemical reaction, such as combustion or oxidation, could possibly explain the vast amounts of energy released by even the smallest star. In 1939, the German-American physicist Hans Bethe worked out the mathematics of energy generation in which a proton first fuses with a **carbon** atom to form a nitrogen atom. The reaction then continues through a series of five more steps, the net result of which is that four protons are consumed in the generation of one helium atom.

Bethe chose this sequence of reactions because it requires less energy than does the direct fusion of four protons and, thus, is more likely to take place in a star. Bethe was able to show that the total amount of energy released by this sequence of reactions was comparable to that which is actually observed in stars.

The Bethe carbon-cycle is by no means the only nuclear fusion reaction. A more direct approach, for example, would be one in which two protons fuse to form a deuteron. That deuteron could then fuse with a third proton to form a helium-3 nucleus. Finally, the helium-3 nucleus could fuse with a fourth proton to form a helium-4 nucleus. The net result of this sequence of reactions would be the combining of four protons (hydrogen nuclei) to form a single helium-4 nucleus. The only net difference between this reaction and Bethe's carbon cycle is the amount of energy involved in the overall set of reactions.

Other fusion reactions include D-D and D-T reactions. The former stands for deuterium-deuterium and involves the combination of two deuterium nuclei to form a helium-3 nucleus and a free neutron. The second reaction stands for deuterium-tritium and involves the combination of a deuterium nucleus and a tritium nucleus to produce a helium-4 nucleus and a free neutron.

The term "less energy" used to describe Bethe's choice of nuclear reactions is relative, however, since huge amounts of energy must be provided in order to bring about any kind of fusion reaction. In fact, the reason that fusion reactions can occur in stars is that the temperatures in their interiors are great enough to provide the energy needed to bring about fusion. Since those temperatures generally amount to a few million degrees, fusion reactions are also known as thermonuclear (thermo = heat) reactions. The heat to drive a thermonuclear reaction is created during the conversion of mass to energy during other thermonuclear reactions.

The understanding that fusion reactions might be responsible for energy production in stars brought the accompanying realization that such reactions might be a very useful source of energy for human needs. The practical problems of building a fusion power plant are incredible, however, and scientists are still a long way from achieving a containment vessel or field in which controlled fusion reactions could take place. A much simpler challenge, however, is to construct a "fusion power plant" that does not need to be controlled, that is, a fusion bomb.

Scientists who worked on the first fission (atomic) bomb during World War II were aware of the potential for building an even more powerful bomb that operated on fusion principles. A fusion bomb uses a fission bomb as a trigger (a source of heat and pressure to create a fusion chain reaction. In the microseconds following a fission explosion, fusion begins to occur within the casing surrounding the fission bomb. Protons, deuterons, and tritons begin fusing with each other, releasing more energy, and initiating other fusion reactions among other hydrogen isotopes. The original explosion of the fission bomb would have ignited a small star-like reaction in the casing surrounding it.

From a military standpoint, the fusion bomb had one powerful advantage over the fission bomb. For technical reasons, there is a limit to the size one can make a fission bomb. However, there is no technical limit on the size of a fusion bomb—one simply makes the casing surrounding the fission bomb larger. On August 20, 1953, the Soviet Union announced the detonation of the world's first fusion bomb. It was about 1,000 times more powerful than was the fission bomb that had been dropped on Hiroshima less than a decade earlier. Since that date, both the Soviet Union (now Russia) and the United States have stockpiled thousands of fusion bombs and fusion missile warheads. The manufacture, maintenance, and destruction of these weapons remain a source of scientific and geopolitical debate.

With research on fusion weapons ongoing, attempts were also being made to develop peaceful uses for nuclear fusion. The containment vessel problems remain daunting because at the temperatures at which fusion occurs, known materials vaporize instantly. Traditionally, two general approaches have been developed to solve this problem: magnetic and inertial containment.

One way to control that plasma is with a **magnetic field**. One can design such a field so that a swirling hot mass of plasma within it can be held in a specified shape. Other proposed methods of control include the use of suspended microballoons that are then bombarded by the laser, electron, or atomic beam to cause implosion. During implosion, enough energy is produced to initiate fusion.

The production of useful nuclear fusion energy depends on three factors: **temperature**, containment time, and energy release. That is, it is first necessary to raise the temperature of the fuel (the hydrogen isotopes) to a temperature of about 100 million degrees. Then, it is necessary to keep the fuel suspended at that temperature long enough for fusion to begin. Finally, some method must be found for tapping off the energy produced by fusion.

In the late twentieth century, scientists began to explore approaches to fusion power that departed from magnetic and inertial confinement concepts. One such approach was called the PBFA process. In this machine, electric charge is allowed to accumulate in capacitors and then discharged in 40-nanosecond micropulses. Lithium ions are accelerated by means of these pulses and forced to collide with deuterium and tritium targets. Fusion among the lithium and hydrogen nuclei takes place, and energy is released. However, the PBFA approach to nuclear fusion has been no more successful than has that of more traditional methods.

In March of 1989, two University of Utah electrochemists, Stanley Pons and Martin Fleischmann, reported that they had obtained evidence for the occurrence of nuclear fusion at room temperatures (i.e., cold fusion). During the electrolysis of heavy **water** (deuterium oxide), it appeared that the fusion of deuterons was made possible by the presence of palladium electrodes used in the reaction. If such an observation could have been confirmed by other scientists, it would have been truly revolutionary. It would have meant that energy could be obtained from fusion reactions at moderate temperatures. The Pons-Fleischmann discovery was the subject of immediate and intense scrutiny by other scientists around the world. It soon became apparent, however, that evidence for cold fusion could not consistently be obtained by other researchers. A number of alternative explanations were developed by scientists for the apparent fusion results that Pons and Fleischmann believed they had obtained and most researchers now assert that Pons and Fleischmann's report of "cold fusion" was an error and that the results reported were due to other chemical reactions that take place during the electrolysis of the heavy water.

See also Atom; Atomic mass and weight; Atomic number; Atomic theory; Big Bang theory; Chemical elements; Chemistry; Electricity and magnetism; Energy transformations; Radioactive waste storage (geological considerations); Radioactivity

NUCLEAR WINTER

Nuclear winter is a theory estimating the global climatic consequences of a nuclear war: prolonged and worldwide cooling and darkening caused by sunlight-blocking smoke and soot entering the atmosphere. During the Cold War after World War II, the concern about nuclear weapons was increasing all over the world. Initially, only the danger of radioactive fallout was recognized, but later also the possible environmental effects of a nuclear war became the subject of several studies. The term nuclear winter was first defined and used by American astronomer **Carl Sagan** (1934–1996) and his group of colleagues in their 1983 article (later referred to as the TTAPS-article, from the initials of the authors' family names). This article was the first one to take into consideration not only the direct damage, but also the indirect effects of a nuclear war.

The basic assumption during a nuclear war is that the exploding nuclear warheads would create huge fires, resulting in smoke and soot from burning cities and **forests** being emitted into the **troposphere** in vast amounts. This would block the sun's incoming radiation from reaching the surface of Earth, causing cooling of the surface temperatures. The smoke and soot soon would rise because of their high **temperature**, allowing them to drift at high altitudes for weeks without being washed out. Finally, the particles would settle in the Northern Hemisphere mid-latitudes as a black particle cloud belt, blocking sunshine for several weeks. The darkness and cold, combined with nuclear fallout radiation, would kill most of Earth's vegetation and animal life, which would lead to starvation and diseases for the human population surviving the nuclear war itself. At the same time, the upper troposphere temperatures would rise because the smoke would absorb sunlight and warm it up, creating a temperature inversion, which would keep **smog** at the lower levels. Another possible consequence is that nuclear explosions would produce nitrogen oxides, which would damage the protective ozone layer in the **stratosphere**, thus allowing more ultraviolet radiation to reach the earth's surface.

Although the basic findings of the original TTAPS-article have been confirmed by later reports, some later studies report a lesser degree of cooling would occur, only around 25 degrees of temperature drop and only for weeks instead of the initially estimated months. According to different scenarios, depending on the number of nuclear explosions, their spatial distribution, targets, and many other factors, this cloud of soot and dust could remain for many months, reducing sunlight almost entirely, and decrease average temperatures to as low as –40°C in the Northern Hemisphere continents. There are other studies, that mention the possibility of a not so severe nuclear winter as originally estimated, hence it is named a nuclear fall. Other researchers even talk about nuclear summer, stating that a worldwide warming would follow a nuclear war because of the many small contributions to the **green-**

house effect from **carbon dioxide**, **water** vapor, **ozone**, and various aerosols entering the troposphere and stratosphere. What all scenarios agree on is that a nuclear war would have a significant effect on the atmosphere and **climate** of the earth and, consequently, many aspects of life such as food production or energy consumption would be drastically effected.

Opponents of the nuclear winter theory argue that there are many problems with the hypothesized scenarios either because of the model's incorrect assumptions (e.g., the results would be right only if exactly the assumed amount of dust would enter the atmosphere, or the model assumes uniformly distributed, constantly injected particles), or because important effects, processes and/or feedback mechanisms are not taken into consideration (e.g., the moderating effects of the **oceans**, or small-scale processes are not included, or the biological effects are not addressed), or simply because there are many uncertainties involved in the estimates. The topic even at present day remains controversial, because the exact level of damage, along with the extent and duration of the effects, cannot be agreed upon with full confidence.

See also Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric lapse rate; Atmospheric pollution

NUCLEATE AND NUCLEATION

A nucleation event is the process of **condensation** or aggregation (gathering) that results in the formation of larger drops or **crystals** around a material that acts as a structural nucleus around which such condensation or aggregation proceeds. Moreover, the introduction of such structural nuclei can often induce the processes of condensation or crystal growth. Accordingly, nucleation is one of the ways that a phase transition can take place in a material.

In addition to an importance in explaining a wide variety of geophysical and geochemical phenomena—including crystal formation—the principles of nucleation were used in **cloud seeding weather** modification experiments where nuclei of inert materials were dispersed into **clouds** with the hopes of inducing condensation and rainfall.

During a phase transition, a material changes from one form to another. For example, **ice** melts to form liquid **water**, or a liquid boils to form a gas. Phase transitions occur due to changes in **temperature**. Certain transitions occur smoothly throughout the whole material, while others happen suddenly at different points in the material. When the transitions occur suddenly, a bubble forms at the point where the transition began, with the new phase inside the bubble and the old phase outside. The bubble expands, converting more and more of the material into the new phase. The creation of a bubble is called a nucleation event.

Phase transitions are grouped into two categories, known as first order transitions and second order transitions. Nucleation events happen in first order transitions. In this kind of transition, there is an obstacle to the transition occurring smoothly. A prime example is condensation of water vapor to form liquid water. Condensation requires that many water molecules collide and stick together almost simultaneously. This requirement for simultaneous collisions presents a temporary but measurable barrier to the formation of a bubble of liquid phase. Following formation, the bubble expands as more water molecules strike the surface of the bubble and are absorbed into the liquid phase. Because of the obstacle to the phase transition, a liquid may exist in its gaseous state even though the temperature is well below the boiling point.

A liquid in this state is said to be supercooled. Accordingly, in order for a liquid to be supercooled, it must be pure, because dust or other impurities act as nucleation centers. If the liquid is very pure, however, it may remain supercooled for a long time. A supercooled state is termed metastable due to its relatively long lifetime.

The other type of phase transition is called second order, and it proceeds simultaneously throughout the whole material. An example of a second order transition is the **melting** of a solid. As the temperature rises, the magnitude of the thermal vibrations of molecules causes the solid to break apart into a liquid form. As long as the solid is in thermal equilibrium and the melting occurs slowly, the transition takes place at the same time everywhere in the solid, rather than taking place through nucleation events at isolated points.

See also Bowen's reaction series; Chemical bonds and physical properties; Chemical elements; Chemistry; Crystals and crystallography; Minerals; Precipitation

NUEE ARDENT

A nuee ardent, or "glowing cloud," is a type of explosive volcanic eruption characterized by a dense, very hot mass of ash, gasses, and volcanic material traveling down a volcanic slope at high velocity. A nuee ardent, also called a pyroclastic flow, can reach speeds of 450 mi/hr (720 km/hr) and temperatures of 1,500°F (830°C). They can travel as much as 124 mi (200 km) from the source and cover areas as large as 12,000 mi^2 (20,000 km^2). The volume of transported material can be as large as 250 mi^3 (1,000 km^3) or more.

Nuees ardentes can be destructive and deadly. An eruption of Mount Pelee, Martinique, in 1920 produced a nuee ardent that, within minutes, killed 30,000 inhabitants of a nearby town. In 1982, eruptions and pyroclastic flows from El Chichòn **Volcano**, southeastern Mexico, killed 2000 people, in villages as far as 5 mi (8 km) from the source.

Nuees ardentes are typically composed of two parts; a basal or lower part that hugs the ground and contains the larger volcanic fragments, and an upper part composed of a turbulent mix of hot ash and gas. When cooled, the gas and ash can form **pumice**, a very porous and lightweight volcanic **rock.**

Pyroclastic flows commonly are produced either by the downslope movement of fragments ejected upwards as they fall back, or by explosive eruptions that pulverize existing rock and throw the rock, ash, and gas in a more horizontal direction. In many cases, pyroclastic flows result from a combination of mechanisms. The sequence of events leading up to and during the 1980 eruption of Mount St. Helens illustrates some of the complexity of the process. An increase in seismic activity beneath the volcano in March marked the beginning phase of the eruption. **Magma** injected into the cone of the volcano at high pressure created a bulge on the north flank that grew outward at rates as high as 8.2 ft (2.5 m) per day. For the next two months only minor eruptions occurred. On May 18, a 5.1 magnitude **earthquake** triggered a series of massive landslides of material over the bulge. Remove of this material destabilized the north slope, which failed explosively releasing a pyroclastic flow horizontally. The eruptions flattened trees and killed wildlife in a 212 mi^2 (550 km^2) **area**. The eruption removed the upper 1,300 ft (400 m) of the cone and left a crater 2,000 ft (625 m) deep, 1.7 mi (2.7 km) long, and 1.3 mi (2.0 km) wide.

O

OBSIDIAN

Obsidian is volcanic **glass** with a chemical composition similar to that of **rhyolite** or **granite**. It is most commonly black, although greenish to reddish and banded varieties also occur. In addition to its dark color and glassy luster, obsidian is characterized by bowl-shaped or concave conchoidal fractures.

In the hands of a skilled practitioner, obsidian can be worked into razor sharp stone tools such as knives and spear points. Thus, obsidian tools are often found during archaeological excavations. Obsidian is also used for scalpel blades by some modern surgeons because obsidian blades can be sharper and thinner than their steel counterparts.

Obsidian is formed from silica-rich **lava** that cools too quickly for **crystals** to grow. The result is a glass that does not possess the regular crystal structure of **minerals** in rhyolite and granite, even though all three have the same general chemical composition. The lack of crystal structure is also responsible for the conchoidal fractures characteristic of obsidian. The dark color of obsidian is due to the presence of **iron** oxide minerals distributed throughout the otherwise clear glass. Magnetite produces black obsidian, whereas more highly oxidized hematite produces reddish varieties. Because its silica content makes it extremely viscous, the rhyolitic lava that freezes into obsidian is extremely resistant to flow and obsidian is most commonly found in small dome-like bodies very close to volcanic vents.

Obsidian artifacts and outcrops can be dated using the thickness of a hydration rind that forms when **water** vapor diffuses into a freshly broken surface. The age of the fresh surface is estimated by comparing the rind thickness with the results of a mathematical model of water vapor diffusion through obsidian. Rind thickness was originally estimated using optical microscopes, but recently developed techniques such as secondary ionization mass spectrometry provide more accurate measurements of the rind thickness. When applied to artifacts, the method gives the age of fractures produced when a human made the tool; when applied to **rock** outcrops, it gives the age of fractures presumably produced during or shortly after the eruption.

See also Dating methods; Minerals; Pumice; Volcanic eruptions; Volcanic vent; Volcano

OCEAN CIRCULATION AND CURRENTS

Ocean circulation is the large, connected system of **water** movements in the **oceans**, including not only the surface movement, but also the slow, deep-water circulations. While the surface currents are caused by the winds and a geographically uneven **solar energy** distribution, the deep ocean currents are the result of sinking and upwelling water, and termohaline (**temperature** and salinity) differences. The atmospheric and oceanic circulations are linked together, and this global ocean circulation system transfers heat from low to higher latitudes, making the oceans responsible for about 40% of the global heat transport. Although there are similarities between the atmospheric and oceanic circulations, ocean currents move slower than winds, with a speed of about several kilometers per day to a few kilometers per hour.

The system of surface currents resembles the major **wind** patterns of the atmosphere. However, the surface currents do not move exactly in the same direction, but at a 45-degree angle to wind direction, with a water speed of less than 3% of the original wind speed. It turns to right on the Northern Hemisphere, and to left on the Southern Hemisphere. Going down to a deeper layer, it tends to turn even further compared to the surface, and going even deeper in the water (until about 109 yd [100 m], where the depth of no motion is reached), eventually, the angle between the surface winds and the deep movements reaches 90 degrees. This is called the Ekman spiral.

The surface currents in each ocean can be described with a simplified scheme (although the actual currents differ in depth, size or exact location). The dominant features are the subtropical gyres (semi-closed circles of the currents), and the boundary currents, both in the east and west ocean basins. The gyres are centered around 30 degrees **latitude** in the major ocean basins, and rotate clockwise in the Northern Hemisphere, and counterclockwise in the Southern Hemisphere because of the earth's **rotation** and the change in wind direction with latitude. The basic ocean circulation looks like a westward flow near the equator, which moves warm water to higher latitudes at the western ocean basins. At about 35 degrees of both North and South latitudes, the major currents turn in an eastern direction, to carry warm water to higher latitudes. To balance this poleward movement at the eastern ocean basins, cold water has to return in the currents. In the Southern Hemisphere, the gyre turns in the opposite direction, and because there is no land between 35 and 60 degrees latitude, a strong, cold current around **Antarctica** completes the system.

The clockwise rotating gyre in the northern part of the Atlantic Ocean consists of the warm North Equatorial Current flowing near the equator, joining the western boundary of the warm **Gulf Stream**, which turns towards east and becomes the warm North Atlantic Drift, while the cold Labrador Current, West Greenland Drift, and East Greenland Drift return cold water from the North. The eastern boundary, the southward Canary Current close to West **Africa** also brings cold water towards the equator, closing the North Atlantic Ocean gyre. In the southern part of the Atlantic Ocean, in the counterclockwise gyre, the warm South Equatorial Current joins the warm Brazil Current going south towards Antarctica at the east coast of **South America**, meeting the cold Falkland Current, and the cold, West Wind Drift going east around Antarctica. The gyre is closed by the cold Benguela Current going north at the southwestern coast of Africa, while the eastward flowing warm Equatorial Countercurrent connects the gyres from the north and South Atlantic Oceans.

The system of currents in the Pacific Ocean is very similar to the Atlantic currents. The clockwise rotating gyre in the northern part of the Pacific Ocean consists of the warm North Equatorial Current flowing westward north of the equator, joining the western boundary warm Kuroshio Current, which turns towards the East and becomes the warm North Pacific Drift, while the cold Oyashio Current returns cold water from the North. At the coast of Alaska loops the warm Alaska Current. The eastern boundary California Current, close to the coast of California, also brings cold water towards the equator, closing the North Atlantic Ocean gyre. This is where upwelling, the rising of cold water replacing surface water that drifts away due to the winds, occurs. Although it brings cold water, low **clouds**, and sometimes **fog** in summer, the nutrient-rich, cold water helps the fishing industry. South of this gyre but still in the Northern Hemisphere, the eastward flowing warm North Equatorial Countercurrent can be found. In the southern part of the Pacific Ocean, the warm, westward South Equatorial Current flows opposite of the eastward warm South Equatorial Countercurrent, and continues towards the South at the east coast of **Australia**. While the West Wind Drift is heading east around the Antarctica, the cold Peru or Humboldt Current going northward at the southwestern coast of South America closes this gyre.

The system of surface ocean currents is simpler in the Indian Ocean, because instead of the "8-shaped" two gyres, only one is present, influenced by seasonally changing winds. It consists of the warm North Equatorial Current, the South Equatorial Countercurrent, the South Equatorial Current, and the eastward, circumpolar current around Antarctica, the cold West Wind Drift.

See also Gulf stream; Oceans and seas

OCEAN TRENCHES

A deep-sea trench is a narrow, elongate, v-shaped depression in the ocean floor. Trenches are the deepest parts of the ocean, and the lowest points on Earth, reaching depths of nearly 7 mi (10 km) below sea level. These long, narrow, curving depressions can be thousands of miles in length, yet as little as 5 mi (8 km) in width. Deep-sea trenches are part of a system of tectonic processes termed subduction. Subduction zones are one type of **convergent plate boundary** where either an oceanic or a continental plate overrides an oceanic plate. A trench is formed where the oceanic plate dives below (is subducted by) the (less dense) overriding plate. They are associated with a certain type of volcanic chain called an island arc and with zones of high **earthquake** activity. The trenches can extend for thousands of kilometers parallel to the volcanoes of the **island arcs** located on the overriding plate. Examples include the Aleutian islands, an arc bordered to the south by the Aleutian trench, and the Marianas, bordered by the Mariana trench, the deepest in the world. Along the western coast of **South America**, the Peru-Chile trench marks where the Nazca plate is being subducted beneath the South American plate. The volcanic activity and uplift of the Andes mountains are a result of the subduction process.

Trenches and active subduction zones are found along much of the Ring of Fire, a zone of volcanism and earthquake activity that borders the Pacific ocean. The tectonic processes of subduction form the trenches and island arcs and are also responsible for the earthquake activity. Major earthquakes occur along the plunging boundary between the subducting and overriding plates. This boundary is called a **Benioff zone**. Many scientists believe that the volcanic island arcs are formed from magmas produced by the **partial melting** of the descending and/or the overriding plate. Considerable volcanic activity worldwide is the result of subduction.

Most geologists argue that the size of the earth has not changed significantly in the past several hundred million years. According to tectonic theory, new **crust** is generated along the divergent plate boundaries such as the mid-Atlantic ridge at rates on the order of a few centimeters a year. As the new crust is created, an equal amount must be destroyed at roughly the same rate for the size of Earth to remain unchanged. Subduction along the trenches of the convergent plate boundaries appears to maintain that balance.

See also Plate tectonics

OCEANIC CRUST • *see* CRUST

OCEANOGRAPHY

Oceanography, the study of the **oceans**, is a combination of the sciences of biology, **chemistry**, **geology**, **physics**, and **meteorology**.

Ancient explorers of the ocean were sailors and fishermen who learned about marine biology by observing the sea life and discovering when it was most plentiful. They observed the effects of **wind**, currents, and **tides**, and learned how to use them to their advantage or to avoid them. These early humans discovered that salt could be retrieved from seaweed and grasses.

Polynesians combined what they knew about the **weather**, winds, and currents to investigate the Pacific Ocean, while the Phoenicians, Greeks, and Arabs explored the Mediterranean Sea. The early Greeks in general and Herodotus (484–428 B.C.) in particular believed that the world was round. Herodotus performed studies of the Mediterranean, which helped sailors of his time. He was able to take depth measurements of the sea floor by using the fathom as a unit of measure, which was the length of a man's outstretched arms. Today the fathom has been standardized to measure 6 ft (1.8 m) in length.

Aristotle (384–322 B.C.) also studied marine life. One of his contemporaries, a geographer by the name of Poseidarius, studied the tides and their relationship to the phases of the **Moon**.

Pliny the Elder (A.D. 23–79) was a Roman naturalist who discovered, by studying marine biology, that some organisms had medicinal uses. One of his predecessors, Seneca (4 B.C.–A.D. 65) predicted that interest in the oceans would fade and "a huge land would be revealed," foreshadowing the age of exploration and discovery of the New World. A period of about 1,000 years followed when no new studies were done until the fifteenth century. Christopher Columbus performed oceanographic studies on his voyages.

Captain **James Cook**, the explorer, was one of the first scientists to study the oceans' natural history. A surge in scientific studies took place in the seventeenth century, during which scientists tried for the first time to combine the **scientific method** with sailors' knowledge.

U.S. Navy lieutenant Matthew Fontaine Maury (1806–1873) is considered the father of modern oceanography. It was during the nineteenth century that the name was given to the science.

In December 1872, the British ship HMS *Challenger* began a four-year journey, which lasted until May of 1876. This was the first major study of the ocean approached from a scientific viewpoint, and since that time significant strides have been made. The advent of submersible vehicles allowed for first-hand study of the ocean floor and the **water** above it. In 1900, Prince Albert of Monaco established two institutes to study oceanography.

Two areas of focus within oceanography today are physical and chemical oceanography. Physical oceanography is the study of ocean basin structures, water and sediment transportation, and the interplay between ocean water, air and sediments and how this relationship affects processes such as tides, upwellings, **temperature**, and salinity. Findings aid oceanic engineers, coastal planners, and military defense strategists. Current areas of research also include oceanic circulation, especially ocean currents and their role in predicting weather-related events, and changes in sea level and climate.

Chemical oceanography investigates the chemical make-up of the oceans. Many studies in this **area** are geared to understanding how to use the oceans' resources to produce food for a growing population.

Even though the study of the oceans has entered the technological age, there is much still unexplored and unknown. Oceanographers of the 1990s use satellites to study changes in salt levels, temperature, currents, biological events, and transportation of sediments. Deep-sea studies are underway using unmanned robotic submersible craft to study ocean floor hydrothermal vents, **sea-floor spreading**, and subduction zones that lie beneath the ocean floor. As scientists develop new technologies, the future will open new doors to the study of oceanography.

See also Bathymetric mapping; Beach and shoreline dynamics; Continental drift theory; Continental shelf; Convergent plate boundary; Coral reefs and corals; Delta; Depositional environments; Desalination; Douglas sea scale; Dunes; Earth (planet); Earth science; Earth, interior structure; El Nino and La Nina phenomena; Geothermal deep ocean vents; Global warming; Gulf of Mexico; Gulf stream; Guyots and atolls; Hawaiian Island formation; History of exploration II (Age of exploration); Hydrogeology; Hydrologic cycle; Hydrothermal processes; Icebergs; Land and sea breeze; Latitude and longitude; Marine transgression and marine regression; Mid-ocean ridges and rifts; Ocean circulation and currents; Ocean trenches; Oceans and seas; Offshore bars; Petroleum; RADAR and SONAR; Red tide; Saltwater encroachment; Seawalls and beach erosion; Tides; Wave motions

OCEANS AND SEAS

Oceans are large bodies of **saltwater** connected together, unevenly covering 70% of the earth, and containing about 97% of Earth's **water** supply as salt water. The five major oceans, in descending order of size by **area**, are the Pacific Ocean (64 million square miles, about 165 million square kilometers), Atlantic Ocean (33 million square miles, about 85 million square kilometers), Indian Ocean (28 million square miles, about 70 million square kilometers), Southern Ocean (almost 8 million square miles, about 20 million square kilometers), and Arctic Ocean (5,000,000 square miles, almost 13 million square kilometers).

The Pacific Ocean is the largest ocean, covering about one third of the earth's surface, which is a bigger area than all of the continents combined. The Pacific Ocean is not only the home of the highest mountain on Earth (Mauna Kea, 33,476 ft, or 10,203 m), but also has the deepest trench (Mariana trench, 36,198 ft, or 11,033 m deep). The Atlantic Ocean is the second largest, covering 20% of Earth's surface. It is also the youngest among the five oceans, and it is the ocean where the most shipping occurs. The third largest ocean is the Indian Ocean, which provides an important trade route between **Africa** and **Asia**, and is home to the most expressed monsoon system. The next in size is the Southern Ocean, which surrounds **Antarctica**, and was officially named in the year 2000 by the International Hydrographic Organization. Finally, the Arctic Ocean is the smallest ocean of all five, but contains the widest **continental shelf**.

Seas are the smaller bodies of salt water connecting the oceans, which can be partially or entirely enclosed by land. Examples of seas adjacent to the oceans include the South China Sea (the largest sea), Caribbean Sea, Mediterranean Sea, Bering Sea, **Gulf of Mexico**, Hudson Bay, Gulf of California, Sea of Japan, and Persian Gulf. Examples of inland seas (or **lakes**) are the Caspian Sea, Sea of Galilee, or Dead Sea.

Earth's oceans and seas are unique in that there is no other planet in our **Solar System** that has liquid water on its surface. Life on Earth began in the oceans, and today they still are the home to some of the most spectacular wildlife in the world. Most of the oceans' wildlife is located in the upper ocean layers, which contain about two percent of the oceans' volume. The oceans also play a significant role in the earth's water cycle. Oceans are a large source of water vapor for the atmosphere, which is important in heat transportation in the atmosphere in the form of latent heat. Additionally, the oceans gather water at the end of the water cycle not only from **precipitation**, but also from surface **runoff** and return flow from **rivers** and as **groundwater** flows from land. The oceans are major reservoirs in the **carbon** cycle. In order to double the current atmospheric **carbon dioxide**, it would be necessary to release only 2% of the carbon currently stored in the oceans.

Oceans produce important and widespread effects on Earth's atmosphere, **weather**, and **climate**. Oceans and land exhibit different heating and cooling properties; **solar energy** penetrates deeper into water than into land, and water can circulate that absorbed heat easily into deeper layers. Because the specific heat of water (the amount of heat required to raise the **temperature** of one gram of water by one degree Celsius) is higher than that of land, it takes about five times more energy to warm up water by one degree Celsius than to equally heat a **rock**. Consequently, oceans not only warm more slowly than land, but also cool more slowly. Oceans, therefore, act as a giant heat reservoir, which heats the land during winter and cools it during summer, moderating the climate of the land located next to it.

Oceans not only moderate the climate of adjacent areas by absorbing and storing solar energy, they also distribute heat between lower and higher latitudes by a global, interconnected system of ocean currents. An example of the climatic effects of oceans on lands is the **Gulf Stream**, which is not only part of the heat redistributing process by carrying warm waters towards higher latitudes, but also brings mild air to the British Isles and Northwest **Europe**, causing a significantly milder climate than it would normally have according to its latitudes.

Interesting examples of the interaction between the oceans and the atmosphere are the **El Niño and La Niña phenomena** patterns. Along with the Southern Oscillation, El Niño and La Niña influence not only nearby areas in the Pacific Ocean, but effect the entire global climate system, along with the ecologies and economies of many countries worldwide, from New Zealand to the United States.

As the oceans and seas are a significant part of the atmosphere and the climate system with many interactions and feedback mechanisms, there is a recent debate about their role in anthropogenic climate change, and also about the possible consequences of climate change for the oceans. Rising sea levels could occur due to both the thermal expansion of the oceans, and from the **partial melting** of the **polar ice** because of **global warming**. Although there is a debate between scientists about the possibility and the intensity of this prediction, if rising sea levels happen at any level, it could be potentially devastating for many coastal cities around the world.

See also El Niño and La Niña phenomena; Hydrologic cycle; Ocean circulation and currents

ODÉN, SVANTE N. F. (1924-1986)

Swedish soil scientist and chemist

Svante Odén is known because of his efforts in the 1960s to publicize the problem of acid rain and connect it with the deterioration of **forests** and fisheries. **Acid rain** was known to European scientists in the seventeenth century, named by Robert Angus Smith (1817–1884) in 1872, and accurately described by Eville Gorham (b. 1925) in the 1950s, but only became a popular environmental concern after the Swedish National Science Research Council published Odén's findings in 1968 as "The Acidification of Air and Precipitation and its Consequences in the Natural Environment" in *Ecology Community Bulletin No. 1.*

Odén was born on April 29, 1924 in Oscar's Parish, Stockholm, Sweden. After passing his upper secondary school examination in 1943, he earned a master of science degree in agriculture in 1954 and a licentiate in agriculture in 1957. He taught **soil** science and ecological **chemistry** at the Swedish University of Agricultural Sciences, Uppsala, for the rest of his career. He disappeared and was presumed dead in 1986.

In 1961, Odén began collecting field data about the relationship between bodies of fresh **water** and surrounding soils. This research, following that of two other Swedes, Carl Gustav Arvid Rossby (1898–1957) and Erik Eriksson at the **Meteorology** Institute of Stockholm University, led him toward analyzing the chemistry of rain and eventually to the retroactive monitoring of air pollutants emitted from several parts of **Europe**. He soon correlated these findings with meteorological evidence and concluded that industrial air pollution, especially sulfur dioxide, from Britain and Germany adversely affected the rain that fell in Sweden.

Comparing his data with that of fisheries inspector Ulf Lunden, Odén became alarmed that the unchecked continuation of this trend could destroy Swedish fish populations and reduce Swedish crop yields. Accordingly, he took the unusual step of publishing his results, not first in a scientific journal, but in a newspaper, the October 24, 1967, issue of *Dagens Nyheter*. The Swedish government and people immediately mobilized behind Odén, and in 1972 the United Nations Conference on the Human Environment, held in Stockholm, reported extensive fish kills, forest and farm damage, and human health problems in Sweden, all related to acid rain.

Sweden was the first country where the study of acid rain was taken seriously. Since much of the Swedish economy centers around fish—and since acid rain can decrease fish populations—Odén's publications in both the scientific and the popular press galvanized public opinion and rallied scientists and politicians to defend and protect Swedish interests. Odén remained a tireless advocate for policy reform regarding acid rain, but sometimes overdramatized the case, for example by claiming that Western Europe was waging "chemical warfare" against Scandinavia. He conducted a lecture tour of the United States in 1971 and spoke at the Nineteenth International Limnological Congress in Winnipeg, Manitoba, in 1974. These trips inspired many American and Canadian scientists to begin studying acid rain.

See also Atmospheric pollution; Forests and deforestation; Freshwater; Groundwater; Hydrologic cycle; Lakes; Precipitation; Rivers; Water pollution; Wind

OFFSHORE BARS

Bars are elongate ridges and mounds of **sand** or gravel deposited beyond a shoreline by currents and waves. The term offshore bar has been used to describe both submerged bars, and emergent islands separated from a shoreline by a lagoon, features more correctly identified as **barrier islands**. Submerged bars are only exposed at low tide, if ever, while barrier islands remain at least partially exposed, even at high tide. Because of this ambiguity, the term offshore bar is no longer used as a descriptor in coastal geomorphology.

Longshore, tidal, and fluvial currents construct submerged bars in shallow **water** coastal environments. The amount of unconsolidated sediment available in a shore-zone system, called its sand budget, determines the number of bars and other depositional features that form along the coastline. A shore-zone system's dominant mode of sediment transport controls the shapes and orientations of its depositional forms, including the types of submerged bars.

Along wave-dominated shorelines, longshore currents carry sand along the shoreface and deposit it in submerged bars parallel to the shore. Because waves almost never approach a shoreline perpendicularly, there is an angle between approaching and retreating waves, and sediment grains move down the beach in a zigzag pattern called **longshore drift**. Wave refraction and surf-zone interaction also create strong longshore currents that transport and deposit sediment parallel to the shore in deeper water. Along coastlines where **tides** are the dominant sediment transport mechanism, bidirectional tidal currents build submerged tidal bars perpendicular to the coastline. Tides also transport sand into and out of coastal lagoons through barrier island inlets, forming submerged mounds called ebb-tidal and flood-tidal deltas on either side of the inlets. Submerged bars also form where **rivers** enter the ocean. When sediment-laden fresh water from a confined channel discharges into an unconfined salt-water ocean basin, the current slows and deposits its coarse-grained sediment, or bed load, at the river mouth. The resulting submerged mound of sand and gravel is called a channel mouth bar.

Wave action, tidal currents and fluvial input each influence a shore-zone to some extent, and the different types of submerged bars—longshore bars, tidal bars, and channel mouth bars—usually coexist in a single depositional environment. Combinations of shore-parallel and shore-perpendicular processes create bars with intermediate curved or obliquely oriented morphologies. All types of submerged bars typically obstruct natural and man-made outlets into the ocean, and are well-known navigational hazards.

See also Beach and shoreline dynamics; Bedforms

OIL • *see* PETROLEUM

OLIGOCENE EPOCH

In **geologic time**, the Oligocene Epoch occurs during the **Tertiary Period** (also sometimes divided or referred to in terms of a Paleogene Period and a Neogene Period) of the **Cenozoic Era** of the **Phanerozoic Eon**. The Oligocene Epoch is the third epoch in the Tertiary Period (in the alternative, the latest (most recent) epoch in the Paleogene Period).

The Oligocene Epoch lasts from approximately 34 million years ago (mya) to 23 mya.

The Oligocene Epoch is further subdivided into (from earliest to most recent) Rupelian (34 mya to 29 mya) and Chattian (29 mya to 23 mya) stages. The Oligocene Epoch was preceded by the **Eocene Epoch** and was followed by the **Miocene Epoch**.

Large impact craters dating to the end of the Eocene Epoch and the start of the start of the Oligocene Epoch are evident in Russia (Popigal crater) and in the Chesapeake Bay of the United States. Craters dating to the end of the Oligocene Epoch and start of the Miocene Epoch can be studied in Northwest Canada and in Logancha, Russia. Volcanic activity also increased during the Oligocene Epoch.

The Oligocene Epoch **climate** was warmer than the modern climate. Evidence of the start of a generalized cooling trend is, however, in accord with the rise of warm-blooded mammals as the dominant land species. The Oligocene Epoch continued to present the slow climatic changes that allowed continued development and diversification of mammals.

Notable finds in the **fossil record** that date to the Oligocene Epoch include Branisella monkeys. The first **fossils** of Australian marsupials date to Oligocene Epoch fossil beds. Roses and orchids appeared by the end of the Oligocene Epoch.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Evolution, evidence of; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Mississippian Period; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Supercontinents; Triassic Period

OLIVINE

The olivines are a class of common silicate **minerals** named for their greenish or olive color. They are glassy, fracture conchoidally (i.e., along curving cleavage surfaces), and are often found in meteorites and in **mafic igneous rocks** such as **basalt**, dunite, gabbro, and **peridotite**.

Like the feldspars, the olivines consist of a **silicon** (Si) and **oxygen** (O) framework interspersed with atoms of a metallic additive, usually magnesium (Mg) or **iron** (Fe) but sometimes calcium (Ca). Forsterite (Mg_2SiO_4) is olivine containing no additive but magnesium, while fayalite (Fe_2SiO_4) is olivine containing no additive but iron. Between these two minerals there is a continuum of olivines containing varying percentages of forsterite and fayalite in solid solution. Olivine with 10–30% fayalite is defined as chrysolite; 30–50%, hyalosiderite; 50–70%, hortonolite; and 70–90%, ferrohortonite. The remainder in all cases is forsterite. An olivine with less than 10% fayalite is classified simply as forsterite, while one with less than 10% forsterite is classified simply as fayalite. Confusingly, the term chrysolite is also sometimes used as a synonym for olivine in general.

Magnesium-rich olivine is the majority ingredient of the **rock** peridotite, the main component of Earth's upper mantle. The interface between the underside of the **crust** and the olivine-rich peridotite of the mantle, is called the **Mohorovicic discontinuity** or Moho for short, and is of great importance in **seismology**. The Moho is generally located at a depth of 3.7 mi (6 km) beneath the **oceans** and 19 mi (30 km) beneath the continents.

Compression of olivine's atomic structure to its spinel phases under extreme pressure causes a second seismic discontinuity at approximately 250 mi (400 km) and a third at approximately 420 mi (670 km). These olivine–spinel phase transitions affect the mechanical properties of the whole mantle, which in turn determine the convective flow processes that drive **plate tectonics** and thus much of the geological history Earth.

Implosive collapse of olivine to spinel in slabs of oceanic crust being subducted rapidly into the mantle may be violent enough to generate deep-focus earthquakes.

Olivine is readily altered to the mineral serpentine by the hydration of its crystal structure by hot (400–800°C) **water**. This process occurs along **mid-ocean ridges** and other places where mafic rock is exposed to superheated water.

Peridot (pronounced PER-ih-do) is a transparent variety of olivine valued as a gemstone. Olivine is used industrially as a lining in furnaces due to its heat resistance.

See also Bowen's reaction series; Earth, interior structure; Mantle plumes

OPHIOLITE SUITES

Since the late 1970s, the term ophiolite has been used to describe sections of oceanic **crust** and upper mantle, along with **sedimentary rocks** deposited on the sea floor, emplaced as thrust slices onto continental **lithosphere**. This process, called obduction, results from continent-continent collision following subduction of oceanic crust and the closure of **oceans** or back-arc basins. A typical ophiolite suite comprises (from base to top):

- Harzburgite, dunite, **peridotite,** and pyroxenite (ultramafic **igneous rocks** composed of varying amounts of **olivine** and pyroxene) representing upper, oceanic mantle. They are commonly altered to the slippery, shiny green-black **rock** serpentinite. Serpentinite is named after its resemblance to the skin of a snake. Indeed, the word ophiolite is derived from the Greek words *ophis*, meaning snake, and *lithos*, meaning stone, because of the presence of serpentinites.
- Iron-titanium and magnesium gabbros. Layered, cumulate-textured gabbros dominate the basal section of oceanic crust. Higher-level gabbros tend to be more massive and associated with plagiogranites.
- Sheeted **mafic** dykes, feeders to overlying volcanics.
- Pillow basalts, formed as **lava** flows on the sea floor. The characteristic pillow shapes result from rapid cooling when lava contacts seawater.
- Radiolarian **chert** and **limestone**, graywacke and mudstone or their metamorphic equivalents **marble**, quartzite and mica schist.

Oceanic crust in ophiolites is produced at spreading centers, above zones of subduction in extensional or transtensional arcs (supra-subduction zone ophiolites), and along some leaky **transform faults**. Ophiolites that lack ultramafic, upper mantle rocks may represent obducted slices of seamounts or oceanic plateaus.

Many ophiolites have undergone high pressure-low **temperature**, blueschist **metamorphism** in subduction zones prior to their emplacement. Blueschists are named after blue-colored glaucophane and other sodium-rich amphiboles formed in rocks of appropriate composition. Eclogite facies metamophism occurs when rocks are subducted to greater depth. In eclogites, pyroxene, olivine, and **plagioclase** recrystallize to sodium-rich pyroxene and garnet. During collision, blueschists plus or minus eclogites are thrust as a series of imbricate slices onto lower-grade, continental rocks. Ophiolites may be overprinted by greenschist facies metamorphic assemblages and exhumed during collapse of a thrust-thickened orogen.

Ophiolites in orogenic (mountain building) belts represent sutures between two continental plates. Their recognition is therefore important in tectonic reconstructions. Ophiolites host a range of mineral deposits. Ultramafic and gabbroic rocks may contain deposits of chromium or platinum-group elements. Chrysotile asbestos occurs in serpentinites. Copper, zinc, cobalt and nickel sulfides (marine exhalatives) may occur in economic amounts. Some ophiolites host shear controlled epithermal or mesothermal gold mineralization.

See also Plate tectonics; Subduction zone

ORDOVICIAN PERIOD

In **geologic time**, the Ordovician Period, the second period of the **Paleozoic Era**, covers the time roughly 505 million years ago (mya) until 438 mya. The name Ordovician derives from that of the Ordovices, an ancient British tribe.

The Ordovician Period spans three epochs. The Lower Ordovician Epoch is the most ancient, followed in sequence by the Middle Ordovician Epoch, and the Upper Ordovician Epoch. The Ordovician Period is divided chronologically (from the most ancient to the most recent) into the Tremadocian, Arenigian, Llanvirnian, Llandeilian, Caradocian and Ashgillian stages.

Much of the continental **crust** that exists now had already been formed by the time of the Ordovician Period and the forces driving **plate tectonics** actively shaped the fusing continental landmasses. Near the margins of the continental landmasses, extensive **orogeny** (mountain building) allowed the development of **mountain chains**.

The **fossil record** provides evidence to support the demarcation of the preceding **Cambrian Period** from the Ordovician Period. Drastic changes of sea levels resulted in massive extinctions among marine organisms. In accord with a mass extinction, many **fossils** dated to the Cambrian Period are not found in Ordovician Period formations.

The fossil record establishes that vertebrates existed during the Ordovician Period. As with the Cambrian Period, the Ordovician Period ended with a mass extinction of nearly a third of all species. This mass extinction, approximately 438 mya, marked the end of the Ordovician Period and the start of the **Silurian Period**.

Although there is no evidence of an occurrence equivalent to the **K-T event**, it is possible that an impact from a large meteorite may have been responsible for the mass extinction marking the end of the Cambrian Period and start of the Ordovician Period. Impact craters dating to the Ordovician Period have been identified in **Australia**.

See also Archean; Cenozoic Era; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Paleocene Epoch; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Proterozoic Era; Quaternary Period; Tertiary Period; Triassic Period

ORIENTATION OF STRATA

Strata are layers of **rock**, whether of sedimentary (e.g., **sandstone** or **limestone**) or of extrusive igneous (e.g., **lava** flow) origin. Sedimentary strata are formed when Earth's **gravity** acts upon particles being transported by **wind**, **water**, or **ice** and pulls them down to the earth's surface, where they form a layer. Sedimentary strata also may form from debris flows and viscous mud flows that move according to gravity. Extrusive igneous strata are formed when Earth's gravity acts upon particles within viscous molten rock and pulls them into a sheet-like or tabular mass called a lava flow. Extrusive igneous strata can also form when pyroclastic material is blown out of a **volcano** and falls to Earth, forming a layer of volcanic debris. All such layers obey the laws of **superposition**, original horizontality, and lateral continuity. Of these laws, original horizontality is most pertinent to this discussion because this law predicts the original orientation of rock strata (horizontal). Horizontal is the original orientation of essentially all rock strata.

For this reason, if rock strata is found with some orientation other than horizontal, a force has acted upon the rock strata to re-orient it (change it from its original state). Re-orientation of rock strata occurs principally due to tectonic forces acting within Earth's **crust**.

Orientation of rock strata is defined as the attitude of layers of rock in three-dimensional **space**. In order to measure the orientation of rock strata, geologists use a system of measure consisting of two different compass bearings and an angular measurement. The first compass bearing is that of **strike**. Strike is defined as the compass bearing, relative to north, of the line of intersection between an imaginary horizontal plane and a dipping rock stratum. The second compass bearing is that of **dip** direction, which is the direction of maximum inclination down from strike (dip direction is always perpendicular to strike). The angular measurement is called dip magnitude, which is the smaller of two angles formed by the intersection of an imaginary horizontal plane and a dipping rock stratum. The compass bearings and angular measurement are made in the field by using a hand-held device called a Brunton compass. In subsurface strata, e.g., layers drilled during **petroleum** exploration, orientation of strata (i.e., **strike and dip** measurements) are made by electrical sensor devices lowered into the drill hole on a cable.

Studies of the orientation of rock strata are useful for helping understand the origin of crustal deformation in general and mountain building in particular. Orientation of rock strata can help geologists deduce the direction and type of stresses in Earth's crust that produced the observed deformation. Orientation of rock strata is studied also for purely practical purposes, e.g., in predicting the distribution of **hydrocarbons**, mineral deposits, or **groundwater** within dipping strata. For example, groundwater will flow down the dip direction within an inclined **aquifer** stratum.

Orientation of strata has a strong effect upon surficial **landforms** developed by **weathering** of stratified rocks. For example, flat-topped hills and mountains (e.g., butte, mesa, and pinnacle) have a flat-lying (i.e., horizontally oriented) layer of relatively insoluble rock on top, which protects weaker, underlying strata from **erosion**. Another example of a landform created by rock strata is the flatiron, which is an asymmetrical hill formed by the upturned edges of a dipping layer (rock stratum).

Orientation of rock strata can pose problems for engineering geologists because contacts between steeply dipping strata (i.e., strata with high dip-magnitude angles) can act as planes of weakness. Such planes can promote rockslides and rock falls, both of which can take lives and damage property due to sudden movement of rock material along detachments formed by weak contacts between rock strata.

The orientation of rock strata can be found on most geological maps. The standard symbol for orientation of rock strata is the strike-dip symbol, which consists of a long bar, parallel to strike, and a short spike, parallel to dip direction. This symbol is two to three millimeters in size on most maps and is printed directly upon the mapped layer or stratum possessing the measured dip and strike.

See also Folds; Plate tectonics

ORIGIN OF LIFE

The origin of life has been a subject of speculation in all known cultures and indeed, all have some sort of creation idea that rationalizes how life arose. In the modern era, this question has been considered in terms of a scientific framework, meaning that it is approached in a manner subject to experimental verification as far as that is possible. Geological formations contain a wealth of information concerning the origin of life on Earth and provide abundant evidence of the relationships between physical and biological evolutionary processes.

Radioactive dating provides evidence that that Earth formed at least 4.6 billion years ago. Yet, the earliest known **fossils** of microorganisms, similar to modern bacteria, are only about 3.5–3.8 billion years old. The earlier prebiotic era (i.e., before life began) left no direct record, and so it cannot be determined from the geologic record exactly how life arose. It is possible, however, to at least demonstrate the kinds of abiotic reactions that may have led to the formation of living systems through laboratory experimentation. It is generally accepted that the development of life occupied three stages: First, chemical evolution, in which simple geologically occurring molecules reacted to form complex organic polymers. Second, collections of these polymers self organized to form replicating entities. At some point in this process, the transition from a lifeless collection of reacting molecules to a living system probably occurred. The third process following organization into simple living systems was biological evolution, which ultimately produced the complex web of modern life.

The underlying biochemical and genetic unity of organisms suggests that life arose only once, or if it arose more than once, the other life forms must have become rapidly extinct. All organisms are made of chemicals rich in the same kinds of carbon-containing, organic compounds. The predominance of **carbon** in living matter is a result of its tremendous chemical versatility compared with all the other elements. Carbon has the unique ability to form a very large number of compounds as a result of its capacity to make as many as four highly stable covalent bonds (including single, double, triple bonds) combined with its ability to form covalently linked carbon-carbon (C—C) chains of unlimited length. The same 20 carbon and nitrogen containing compounds called amino acids combine to make up the enormous diversity of proteins occurring in living things. Moreover, all organisms have their genetic blueprint encoded in nucleic acids, either DNA or RNA. Nucleic acids contain the information needed to synthesize specific proteins from their amino acid components. Enzymes, catalytic proteins, which increase the speed of specific chemical reactions, regulate the activity of nucleic acids and other biochemical functions essential to life, while other proteins provide the structural framework of cells. These two types of molecules, nucleic acids and proteins, are essential enough to all organisms that they, or closely related compounds, must also have been present in the first life forms.

Scientists suspect that the primordial Earth's atmosphere was very different from what it is today. The modern atmosphere with its 79% nitrogen, 20% **oxygen**, and trace quantities of other gases is an oxidizing atmosphere. The primordial atmosphere is generally believed not to have contained significant quantities of oxygen, having instead rather small amounts of gases such as carbon monoxide, methane, ammonia and sulphate in addition to the **water**, nitrogen and **carbon dioxide** that it still contains today. With these combinations of gases, the atmosphere at that time would have been a reducing atmosphere providing the hydrogen atoms for the synthesis of compounds needed to create life. In the 1920s, the Soviet scientist Aleksander Oparin (1894–1980) and the British scientist J.B.S. Haldane (1892–1964) independently suggested that ultraviolet (UV) light, which today is largely absorbed by the ozone layer in the higher atmosphere, or violent **lightning** discharges, caused molecules of the primordial reducing atmosphere to react and form simple organic compounds (e.g., amino acids, nucleic acids and sugars). The possibility of such a process was demonstrated in 1953 by Stanley Millar and **Harold Urey**, who simulated the effects of lightning storms in a primordial atmosphere by subjecting a refluxing mixture of water, methane, ammonia and hydrogen to an electric discharge for about a week. The resulting solution contained significant amounts of water-soluble organic compounds including amino acids.

The American scientist, Norman H. Horowitz proposed several criteria for living systems, saying that they all must exhibit replication, catalysis and mutability. One of the chief features of living organisms is their ability to replicate. The primordial self-replicating systems are widely believed to have been nucleic acids, like DNA and RNA, because they could direct the synthesis of molecules complementary to themselves. One hypothesis for the evolution of self-replicating systems is that they initially consisted entirely of RNA. This idea is based on the observation that certain species of ribosomal RNA exhibit enzyme-like catalytic properties and also all nucleic acids are prone to mutation. Thus RNA can demonstrate the three Horowitz criteria and the primordial world may well have been an "RNA world." A cooperative relationship between RNA and protein could have arisen when these self-replicating protoribosomes evolved the ability to influence the synthesis of proteins that increased the efficiency and accuracy of RNA synthesis. All these ideas suggest that RNA was the primary substance of life and the later participation of DNA and proteins were later refinements that increased the survival potential of an already self-replicating living system. Such a primordial pond where all these reactions were evolving eventually generated compartmentalization amongst its components. How such cell boundaries formed is not known, though one plausible theory holds that membranes first arose as empty vesicles whose exteriors served as attachment sites for entities such as enzymes and chromosomes in ways that facilitated their function.

See also Atmospheric chemistry; Cambrian Period; Carbon dating; Earth (planet); Evolution, evidence of; Evolutionary mechanisms; Evolution; Geologic time; Miller-Urey experiment; Precambrian; Uniformitarianism

OROGENY

The terms orogeny and orogenesis are synonymous for tectonic processes that result in the formation of **mountain chains**. Orogeny and orogenesis are derived from the Greek words *oros*, meaning mountain, and *geneia*, meaning born. Orogeny can also have a time connotation when used in naming periods of intense tectonic activity and mountain building, whilst orogenesis is only used to describe the process. For example, "Grenvillian Orogeny" is used to refer to the period of orogenesis in many parts of the world approximately one billion years ago, synchronous with the collision between Laurentia and Baltica in the Grenville Province of **North America**. Areas in which mountain building have occurred in the past, although no mountains may remain today, are called orogens or orogenic belts.

Orogeny or orogenesis most commonly involves the collision between two continental **lithospheric plates** or the collision between a continental plate and an island arc. When a continent collides with an island arc, arc rocks are thrust over continental **crust**. In some orogens (including the Grenville Province), collision between a continental plate and one or more **island arcs** has occurred prior to final continent-continent collision. Collision follows subduction of oceanic **lithosphere** beneath one continent (or possibly even both continents), or a continent and an island arc. Subduction progressively closes the ocean that previously separated them. Continental crust may be partially subducted following ocean closure. Evidence for this comes from deep reflection seismic profiles and seismic tomographic images. High-pressure metamorphic **minerals** such as coesite and glaucophane in exhumed continental crust formed during subduction. In continent-continent collisions, oceanic upper mantle and crust, along with sediments deposited on the seafloor and in the trench above the **subduction zone**, are thrust over continental crust as a series of imbricate slices in a process called obduction. The former oceanic material (collectively called an ophiolite) marks the suture between the two plates. Ophiolitic rocks may be overthrust by continental crust of the colliding plate. Continued shortening (resulting from protracted convergence following plate collision) further deforms the orogen. Early-formed thrust slices are folded and thrusts developed with both the same and opposite sense of tectonic transport to earlier thrusts. In transpressional orogens (e.g., the Mesoproterozoic Albany Mobile Belt of Western **Australia** or the Tertiary Spitsbergen fold and thrust belt, Svalbard, Norway), lateral displacement between plates occurs in addition to folding and thrusting. Transpressional orogens are created by the oblique convergence between two continental plates and do not necessitate closure of an ocean.

Both upper and exhumed lower crustal rocks in collisional and transpressional orogens frequently display evidence for late orogenic extension, or cyclic changes between regional shortening and extension. Uplifted, upper crust may collapse along normal faults and extensional detachments as a result of gravitational instability. Gravitational collapse of upper crustal rocks may take place even though regional shortening continues at deeper crustal levels. Faults formed during gravitational collapse may trend parallel, orthogonal or oblique to earlier-formed thrust faults. Extension in the middle to lower crust in a thrust-thickened orogen may result from convective removal or peeling away (delamination) of part of a lithospheric root. Extension may also be induced by gravitational instabilities within the lower crust. Where the thickened crustal root comprises buoyant material, lateral and upward **gravity** spreading of the lower crust (root rebound) results in horizontal flattening and formation of shallow extensional ductile **shear zones**. Late- to post-orogenic granitoids that intrude as large batholiths or as sheet-like bodies along older shear zones result from **partial melting** of the extended crust. In **Precambrian** orogens, AMCG-suite rocks (anorthosite-mangerite-charnockite-granodiorite) are also commonly the product of late-orogenic extension.

See also Mountain chains; Plate tectonics

ORTELIUS, ABRAHAM (1527-1598)

Belgian cartographer, geographer, and archaeologist

Commercially the most successful cartographer of his time, Ortelius satisfied the ever increasing demand for more and better maps during the Age of Exploration and pushed accurate mapmaking toward the status of fine art.

Ortelius is variously known as "Oertel," "Wortel," "Wortels," ‘‘Ortel," "Ortels," "Ortello," "Ortellius," and even "Portello." Born on either April 14 or 4, 1527, in Antwerp, Belgium, the son of a rich merchant from Augsburg, Germany, he began selling maps as a young boy and joined the chart colorers guild of St. Luke when he was 20. Some historians speculate that he may have had to work to help support his family after his father died in 1535, but there is little evidence for that speculation. It was common then for children of the merchant class to begin learning a trade at a very early age.

Ortelius's mercantile shrewdness, artistic talent, and technical mapmaking skill made him successful by the 1550s. He contracted as an engraver for one of the most important early printers, Christophe Plantin (1520–1589). He traveled widely, conducting business throughout Germany and the Low Countries. In 1559 and 1560, he toured France with his new friend **Gerhard Mercator** (1512–1594), who encouraged him to make original maps, rather than just copies. Inspired by Mercator and urged by map aficionado and merchant Gillis Hooftman (1520?–1581) and Hooftman's protégé, Johan Radermacher de Oude (1538–1617), Ortelius envisioned greater works and began to create them.

In 1570, Plantin published Ortelius's major work, *Theatrum orbis terrarum* (Theatre of the lands of the world), which contained 70 maps on 53 sheets with accompanying text. A book of maps was not called an "atlas" until 1585, when Mercator coined the term for that purpose, but the *Theatrum* was the first modern atlas of the world. Subsequent editions had more maps and it was in print long into the next century, edited by the Flemish engraver Joan Babtista de Vrients (1552–1612) after Ortelius's death. Among the most useful features of the *Theatrum* is Ortelius's historical synopsis of eighty-seven of his predecessors. In many cases, his words are all that is now known about these early cartographers.

In 1575, King Philip II of Spain rewarded Ortelius for the *Theatrum* by appointing him royal geographer, but only after the influential Spanish Benedictine monk, Benedictus Arias Montanus (1527–1598), had assured Philip that Ortelius was a Roman Catholic. Philip's patronage made Ortelius rich.

During Ortelius's lifetime, his atlases sold better than Mercator's. He was not an innovative mathematical cartographer like Mercator, but was a better artist, and an expert at editing, updating, and accurately presenting the data of explorers, geographers, and previous cartographers as far back as **Ptolemy** (fl. ca. 130). A broadly learned man, he kept company with scholars and corresponded with the Catholic humanist Justus Lipsius (1547–1606). In 1577, he toured the British Isles and met the most prominent British and Irish geographers. Among his other publications was the *Thesaurus geographicus* (Geographical treasury) in 1587. He died in Antwerp on either July 4 or June 28, 1598.

See also Cartography; History of exploration II (Age of exploration); Mapping techniques

OWEN, SIR RICHARD (1804-1892)

English biologist

Sir Richard Owen was a comparative anatomist, paleontologist, and zoologist who originated the term "dinosaurus." After insisting that a group of **fossils** he observed belonged to a separate taxonomic order of extinct reptiles unrecognized at the time, Owen named the animal by combining the Greek words "deinos" for terrible and awe-inspiring with "sauros" meaning lizard. Owen noticed that the dinosaur sacral vertebrae were fused, thereby allowing the animal exceptional strength.

Owen was the Hunterian Professor of Comparative Anatomy and Physiology at the Royal College of Surgeons, London, from 1836 to 1856. He then became the superintendent of the Natural History Section of the British Museum in London in 1849, and was superintendent of the entire museum from 1856 to 1883. He is best known as an influential paleontologist during an exciting time in the nineteenth century, when the fossils of extinct dinosaurs were first discovered and their significance in chronicling Earth's biological history began to be understood. In coining the word "dinosaur," Owen and was largely responsible for kindling the dinosaur mania that began in the mid-nineteenth century, and continues today. His first, great popularizing event was the erection of a series of life-sized models of dinosaurs and other extinct creatures at the Crystal Palace in London in 1854, which created an absolute sensation among the Victorian population. Remarkably, a formal dinner partly was held within the body of one of the giant dinosaurs, a model of Iguanodon, as it was nearing completion. Owen sat at the "head" of the table, in the head of the dinosaur.

Along with his extensive work on extinct species of vertebrates, Owen also conducted some important studies of living animals. One of his works involved the confirmation of the earlier observations of James Paget, that the deadly parasite *Trichina spiralis* was the cause of trichinosis in humans, and was transmitted by eating inadequately cooked pork.

Owen was a strong opponent of the theory of Charles Darwin concerning natural selection as a critical force of **evolution**. Throughout his life, Owen refused to accept Darwinian evolution, but modified his anti-evolution views by the mid-1840s. Because of his extensive observations in comparative vertebrate anatomy, Owen eventually asserted that all vertebrate animals evolved from the same archetype, or prototype, that was inspired and created by God. Darwin's most outspoken ally, Thomas Henry Huxley, sparked a 20-year debate with Owen on the principles of evolution that exceeded scientific circles, capturing the attention of Victorian writers, artists, philosophers, and the public at large.

See also Evolution, evidence of; Evolutionary mechanisms; Fossil record; Fossils and fossilization

OUTER CORE • *see* EARTH, INTERIOR STRUCTURE

OXBOW LAKES • *see* CHANNEL PATTERNS

OXIDATION-REDUCTION REACTION

Oxidation-reduction reactions are significant to many geochemical reactions (e.g., the production of **natural gas**). In addition, oxidation-reduction reactions are critical in many carbon-based biological processes.

The term oxidation was originally used to describe reactions in which an element combines with **oxygen**. In contrast, reduction meant the removal of oxygen. By the turn of this century, it became apparent that oxidation always seemed to involve the loss of electrons and did not always involve oxygen. In general, oxidation-reduction reactions involve the exchange of electrons between two species.

An oxidation reaction is defined as the loss of electrons, while a reduction reaction is defined as the gain of electrons. The two reactions always occur together and in chemically equivalent quantities. Thus, the number of electrons lost by one chemical species (a variation of an element or chemical compound) is always equal to the number of electrons gain by another chemical species. The combination of the two reactions is known as a redox reaction. Chemical species that participate in redox reactions are described as either reducing or oxidizing agents. An oxidizing agent is a chemical species that causes the oxidation of another chemical species. The oxidizing agent accomplishes this by accepting electrons in a reaction. A reducing agent causes the reduction of another chemical species by donating electrons to the reaction.

In general, a strong oxidizing agent is a species that has an attraction for electrons and can oxidize another chemical species. The standard voltage reduction of an oxidizing agent is a measure of the strength of the oxidizing agent. The more positive the chemical species' standard reduction potential, the stronger the chemical species is as an oxidizing agent.

In reactions where the reactants and products are not ionic, there is still a transfer of electrons between chemical species. Chemists have devised a way to keep track of electrons during chemical reactions where the charge on the atoms is not readily apparent. Charges on atoms within compounds are assigned oxidation states (or oxidation numbers). An oxidation number is defined by a set of rules that describes how to divide up electrons shared within compounds. Oxidation is defined as an increase in oxidation state, while reduction is defined as a decrease in oxidation state. Because an oxidizing agent accepts electrons from another chemical species, a component **atom** of the oxidizing agent will decrease in oxidation number during the redox reaction.

There are many examples of oxidation-reduction reactions in the world. Important processes that involve oxidation-reduction reactions include combustion reactions that convert energy stored in **fuels** into thermal energy, the **corrosion** of **metals**, and metabolic reactions.

Oxidation-reduction reactions occur in both physical and biological settings (where carbon-containing compounds such as carbohydrates are oxidized). The burning of natural gas is an oxidation-reduction reaction that releases energy [$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$ + energy]. In many organisms, including humans, redox reactions burn carbohydrates that provide energy [$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$]. In both examples, the carbon-containing compound is oxidized, and the oxygen is reduced.

See also Chemical bonds and physical properties; Chemical elements; Chemistry

OXYGEN

Oxygen is the simplest group VIA element and is, under normal atmospheric conditions, usually found as a colorless, odorless, and tasteless gas. Oxygen has an **atomic number** of 8 and an **atomic mass** of 16.0 amu. The liquid and solid forms, which are strongly paramagnetic, are a pale blue color. Oxygen has a boiling point of –297°F (–182.8°C) and a **melting** point of –368.7°F (–222.6°C).

Oxygen is the third most abundant element found in the **Sun**, after hydrogen and helium, and plays an important role in the carbon-nitrogen cycle. Oxygen composes 21% of Earth's atmosphere by volume and is vital to the existence of carbon-based life forms.

Although English chemist Joseph Priestley (1733–1804) is generally credited with the discovery of oxygen in 1774, many science historians contend that Swedish chemist Carl Scheele (1742–1786) probably discovered oxygen a few years prior to Priestly. French chemist Antoine Lavoisier's (1743–1794) contributions to the study of the important reactions, combustion and oxidation, were spurred by the discovery of oxygen. Lavoisier noticed that something was absorbed when combustion took place and that it was obtained from the surrounding air. Lavoisier noted that the increase in the weight of the substance burned was equal to the decrease in the weight of the air used. His studies lead to Lavoisier's oxidation theory, which eventually superseded the phlogistonists' theory (i.e., that every combustible substance was thought to contain a phlogiston, or inherent principal of fire, liberated through burning, along with a residue) that was widely accepted at that time. Lavoisier eventually named the gas he studied oxygen from the Greek *oxys* meaning acid or sharp, and *geinomial* meaning forming. Lavoisier named the gas oxygen because he noted that the burned materials were converted into acids.

Although oxygen has nine isotopes, natural oxygen is a mixture of only three of these. The most abundant isotope, oxygen-18, is stable and available commercially. The most common use for commercial oxygen gas is in enrichment of steel blast furnaces and for medical purposes. Large quantities are also used in making synthetic ammonia gas, methanol and ethylene oxide. Oxygen is also consumed in oxy-acetylene welding. Most commercial oxygen is produced in air separation plants. It is estimated that the United States consumes 20 million tons of oxygen in commercial use per year and the demand is expected to increase dramatically.

When oxygen is exposed to ultraviolet light, as from the Sun, or an electrical discharge, as from lightening, **ozone** (O_3) is formed. Although ozone is toxic to breathe, the 0.12 in (3 mm) thick layer of ozone in the earth's atmosphere provides a shield from harmful **ultraviolet rays** from the Sun. The ozone layer has recently been the subject of intense scientific interest to determine whether, and to what extent, it may be deteriorating, mainly from pollutants in the atmosphere. Unlike pure oxygen gas, ozone has a bluish color and its liquid and solid forms are bluish black to violet-black.

See also Atmospheric chemistry; Atmospheric composition and structure; Global warming; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ozone layer depletion

OZONE

The name ozone comes from the Greek *Ozon* meaning smell. At atmospheric temperatures, ozone is a colorless gas with an odor similar to chlorine that can usually be detected at a level of about 0.01 parts per million.

High in the atmosphere, ozone plays an important protective role by diminishing the amount of potentially damaging ultraviolet radiation reaching Earth. In sufficient concentration, however, ozone is a poison that at lower atmospheric levels, is a pollutant that can be damaging to health. Ozone is also a strong oxidizing agent used in many industrial processes for bleaching and sterilization. Although ozone is often used in **water** treatment, the largest commercial application of ozone is in the production of pharmaceuticals, synthetic lubricants, and other commercially useful organic compounds.

In the atmosphere, ozone is formed predominantly by electric discharges (e.g., **lightning**). In the laboratory, ozone can be extracted form a mixture of **oxygen** and ozone by fractionation.

Ozone can also be formed by ultraviolet light. Ultraviolet light is energetic, and when it strikes the atmosphere it can break down some oxygen molecules producing highly energized oxygen atoms (free radicals). These free radicals can then react with molecular oxygen to produce ozone. The absorption of energetic light radiation also triggers the decomposition of ozone. As a result, ozone is an unstable molecule that exists in a dynamic equilibrium of formation and destruction. Consequently, the protective ozone layer is also in dynamic equilibrium.

The **area** where ozone is formed at the fastest rate is in the atmosphere at a height of approximately 164,042 ft (50 km). At this height, the number of free radicals made by ultraviolet light and electric discharge is balanced by the concentration of diatomic oxygen, which is sufficiently high to ensure that reactive collisions occur.

The protective ozone layer is found in the upper reaches of the atmosphere (between 98,000–295,000 ft [30–90 km]) where it absorbs ultraviolet radiation that, in excess, can be harmful to biological organisms. The potential detrimental effects of increased exposure to ultraviolet light due to a lessening of atmospheric ozone are of great concern. Holes in the ozone layer, or a global breakdown of stratospheric ozone would lead to increasing doses of ultraviolet radiation at Earth's surface. Scientists fear that significant increases exposure to ultraviolet light will increase risks of cancer in animal skin, eyes, and immune systems. Studies have shown that high ultraviolet radiation doses can supply the needed energy for chemical reactions that produce highly reactive radicals that have the potential to damage DNA and other cell regulating chemicals and structures.

There are several atmospheric trace elements, including ozone, that are important in the regulation of the global **climate**. Although the atmosphere consists of mainly of nitrogen and oxygen, approximately one percent of Earth's atmosphere is made of small amounts of other gases. Trace gases include water vapor, **carbon dioxide**, nitrous oxide, methane, chlorofluorocarbons (CFCs), and ozone. Because the amount of trace gases in the atmosphere is small, human activities can significantly affect the proportions of atmospheric trace gases.

Chloroflourocarbons (CFCs) easily react with ozone, which has the effect of breaking down an already unstable molecule. Until recently, CFCs were commonly used in refrigeration and in aerosol propellants (a pressurized gas used to propel substances out of a container). After evidence indicating that the use of CFCs was tipping the ozone equilibrium toward overall **ozone layer depletion**, many industrialized countries opted to enforce restrictions on the use of CFCs. Consumer aerosol products in the United States have not used ozone-depleting substances such as CFCs since the late 1970s. Federal regulations, including the Clean Air Act and Environmental Protection Agency (EPA) regulations restrict the use of ozone-depleting substances.

Ozone played a critical role in the development of life on Earth. Once primitive plants evolved, oxygen started to accumulate in the atmosphere. Some of this oxygen was converted into ozone and the developing ozone layer gave needed protection from disruptively energetic ultraviolet radiation. As a consequence, complex organic molecules which would otherwise have been destroyed began to accumulate.

As well as being found high in the atmosphere, ozone can be found at ground level. At these locations it is regarded as a pollutant. Ozone at ground level can be manufactured as part of photochemical **smog**. This is brought about by the disassociation of oxides of nitrogen that produce oxygen free radicals. These free radicals can react with diatomic oxygen to produce ozone. Pollutant ozone can also be a by-product of the action of photocopiers and computer printers. Low level ozone is usually found at a concentration of less than 0.01 parts per million, whereas in photochemical smog, it can be encountered at levels as high as 0.5 parts per million. Levels of ozone exposure between 0.1 and 1 part per million cause headaches, burning eyes, and irritation to the respiratory passages in humans. Elderly people, asthma sufferers, and those exercising in photochemical smog suffer the greatest adverse effects.

Some plant species (e.g., the tobacco plant) are particularly sensitive to low-lying ozone. The presence of excessive ozone causes a characteristic spotting of the leaves. High ozone levels are also known to damage structural material such as rubber.

Replacing more dangerous chlorine gas, ozone is used in many waste treatment facilities to purify water. Ozone is responsible for disinfecting the water and the efficient removal of trace elements such as pesticides. Ozone kills bacteria and other small life forms and it reacts with organic compounds. During the process, the ozone is transformed to molecular oxygen.

See also Atmospheric pollution; Ozone layer and ozone hole dynamics

OZONE LAYER AND OZONE HOLE DYNAMICS

In 1985, atmospheric scientists discovered that stratospheric **ozone** over **Antarctica** had been reduced to half its natural level. This local loss, termed the Antarctic ozone hole, was traced to destruction of stratospheric ozone by human-made chemicals, especially chlorofluorocarbons (CFCs; artificial compounds consisting of chlorine, fluorine, and **carbon** and widely used as refrigerants and aerosol spray propellants). Other evidence indicates that ozone levels potentially declining over other regions, though nowhere as drastically as over Antarctica.

The ozone hole covers an **area** over the Antarctic continent, the surrounding ocean, the southern tip of **South America** in which stratospheric ozone begins to diminish every August (at the beginning of the Southern hemisphere's spring season), reaches a minimum of less than 50% of its natural value in October, and returns to normal levels by the beginning of December.

Essential to the formation of the Antarctic ozone hole is the polar vortex, which forms every winter over the South Pole. The pole is in 24-hour darkness in midwinter, so the air above it becomes very cold. Cooling air lowers its pressure. Air nearer the equator, warmer and therefore at higher pressure, is sucked toward the pole by the low pressure there. As this warm air moves southward it is twirled into a circular **wind** by the spin of the earth. This circular wind, the polar vortex, sits over the South Pole like a halo, isolating the air over the pole and allowing it to become even colder. Intermittently, the **stratosphere** over the pole becomes cold enough to form **clouds**. The droplets and **ice crystals** in these stratospheric clouds accelerate the breakdown of ozone by chlorine, essentially eliminating ozone from the lower stratosphere and allowing twice the usual amount of UV-B to reach the surface.

No ozone hole forms at the North Pole because the north-polar winter vortex is smaller and warmer than the southern one. There is nevertheless a 30% decline in north-polar ozone every March. Ozone levels have also declined by 3–6% over the inhabited (middle) latitudes, allowing more UV-B to reach the surface and increasing skin cancer rates.

The ozone layer protects the earth by absorbing UV-B, which can cause skin cancer and eye damage. Low-altitude ozone, however, blocks little UV-B and is toxic to plant and animal life.

Ozone (O_3) is a trace ingredient of the atmosphere that stops most solar radiation in the 280–315-nm ultraviolet (UV-B) band from reaching the ground. Ozone is produced in the stratosphere by the breakup of molecular **oxygen** (O_2) by solar radiation. It is also produced artificially in the lower atmosphere (**troposphere**) by the burning of **coal** and gasoline. Ninety percent of the atmosphere's ozone is concentrated in the lower stratosphere, about 6–30 miles (10–50 km) up; this concentration of ozone is the ozonosphere or ozone layer.

Ozone is formed in the stratosphere when an O_2 molecule is split by a photon in the 175–242-nm ultraviolet band (1 nm[nanometer] = 10^{-9} m.) Each O then joins with an O_2 to form an O_3 (ozone) molecule. Ozone converts the energy it gains from absorbing ultraviolet (and infrared) photons into heat, supplying an average 15 watts of power to every square meter of the stratosphere. This ozone-driven heating defines the temperature-versus-altitude structure of the stratosphere.

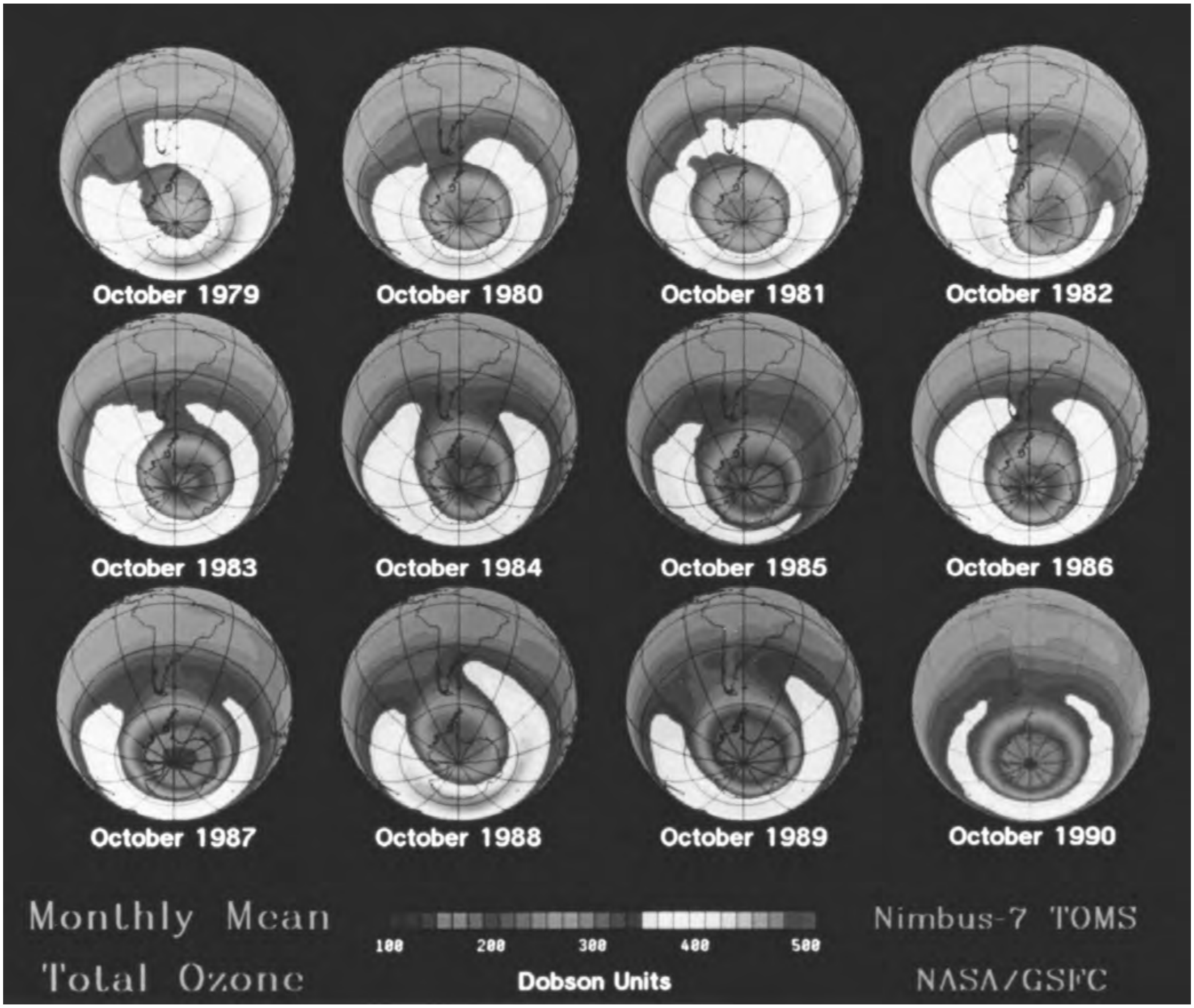
Because ozone is created by sunlight it forms more rapidly over the tropics, where there is more sunlight per square meter. Some ozone created at tropical latitudes circulates through the upper stratosphere to the polar regions, but natural polar ozone levels remain lower than tropical levels. This contributes to the greater vulnerability of the polar regions to ozone depletion by CFCs and other chemicals, discussed below.

Ozone is destroyed primarily by the ClO (chlorine oxide) radical that is produced by the breakdown by sunlight of more complex chlorine-bearing molecules. ClO facilitates the reaction, participating as a catalyst. ClO radicals are free to facilitate reactions again and again. This catalytic persistence explains how minute concentrations of a human-made substance can alter the **chemistry** of an entire layer of the atmosphere: ozone is a million or so times more abundant in the stratosphere than ClO, but each ClO radical destroys thousands of ozone molecules.

Not all chlorine-containing compounds threaten the ozone layer, because not all are capable of reaching the stratosphere. Only non-water-soluble compounds such as CFCs, carbon tetrachloride (CCl_4), and methyl chloroform (CH_3CCl_3) can evade **water** capture in the troposphere and eventually circulate to the ozone layer. There they last anywhere from 5 years (methyl chloroform) to 100 years (CFC-12). CFC-F11 (CCl_3F), the primary contributor to stratospheric chlorine and therefore to ozone loss, has a lifetime of 45 years in the stratosphere.

CFCs are not the only compounds that affect stratospheric ozone; nitrous oxide (N_2O), the bromine-containing compounds termed halons, and methane (CH_4), also do so. Sulfur dioxide (SO_2) injected into the stratosphere by violent **volcanic eruptions**, such as that of Mt. Pinatubo in 1991, can cause significant, albeit temporary, drops in global stratospheric ozone.

In 1987, over 100 nations signed an international agreement to reduce emissions of CFCs and other ozone-depleting chemicals, the Montreal Protocol. Later amendments to the Protocol greatly increased its effectiveness, and today scientists estimate that with strict observance of the Protocol, and barring unforeseen side effects of global **climate** change, stratospheric ozone will cease to decline at some point in the next 10–20 years and recover to 1980 levels by about 2050.



False color images showing ozone depletion from October 1979 to October 1990. ***U.S. National Aeronautics and Space Administration (NASA).***

See also Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Atmospheric pollution; Atmospheric pressure

OZONE LAYER DEPLETION

The ozone layer is a part of the atmosphere between 18.6 mi and 55.8 mi (30 and 90 km) above the ground. The **ozone** present is responsible for blocking potentially harmful ultraviolet radiation reaching the surface of the earth. During the last twenty years, evidence has accumulated that human activity may be the cause of a generalized depletion of the ozone layer. This phenomena is global and distinct from the natural factors that induce annual ozone layer hole formation over **Antarctica**.

Ozone is constantly created and destroyed in natural processes (manufactured by the action of **lightning** on **oxygen** and destroyed by the action of ultraviolet radiation), however the amounts normally balance each other out so there is no net increase or decrease due to natural processes. In 1970, Paul Crutzen showed that naturally occurring oxides of nitrogen can catalytically destroy ozone. In 1974, **F. Sherwood Rowland** and **Mario Molina** demonstrated that chlorofluorcarbons (CFCs) could also destroy ozone. In 1995, all three were jointly awarded the Nobel Prize for chemistry.

The CFCs that were observed as being damaging included Freon 11 ($CFCl_3$) and Freon 12 (CF_2Cl_2). These chemicals are widely used in industry and the home. They have uses as propellants in aerosol spray cans, refrigerant gases, and foaming agents for blown plastics. One problem associated with these gases is their relative lack of reactivity.

When released there is very little that will break them down and, as they are not soluble in **water**, they are not removed from the atmosphere by rain. As a consequence, once released they tend to concentrate in the upper regions of the atmosphere. It is estimated that some several million tons of CFCs are present in the atmosphere.

Once in the upper atmosphere the CFCs are exposed to high energy radiation that can cause disassociation of the molecule, producing free chlorine atoms. This atomic chlorine reacts readily with ozone to produce chlorine monoxide and molecular oxygen. The chlorine monoxide can further react to produce molecular oxygen and more atomic chlorine. This all accelerates the destruction of ozone beyond its natural ability to regenerate. Overall, there is a net reduction in the amount of ozone present in the upper atmosphere. This has led to a thinning of the ozone layer. The majority of this loss is at an altitude between 7.44 mi and 18.6 mi (12 and 30 km) and in the late 1990s evidence was seen that suggested losses were also occurring at other altitudes. In addition to the annual holes in the ozone layer now detected over Antarctica, in the late 1990s, holes were detected over **Australia** and atmospheric sampling indicated a dramatic thinning of the ozone layer in the Northern Hemisphere during the winter months. In the Northern Hemisphere losses of some 30% have been recorded at an altitude of 12.4 mi (20 km).

In 1987, the Montreal Protocol was signed with the appropriate countries agreeing to reduce CFC production. By 1996, more than 100 countries agreed to cease widespread commercial use of CFCs and to stop or curtail production of CFCs.

In the absence of the ozone layer, harmful ultraviolet radiation is able to reach the surface of the earth in higher doses. This can lead to increases in skin cancers.

See also Atmospheric chemistry; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ultraviolet rays and radiation

P

PACIFIC OCEAN • *see* OCEANS AND SEAS

PAHOEHOE FLOW • *see* LAVA

PALEOCENE EPOCH

In **geologic time**, the Paleocene Epoch occurs during the **Tertiary Period** (also sometimes divided or referred to in terms of a Paleogene Period and a Neogene Period instead of a Tertiary Period) of the **Cenozoic Era** of the **Phanerozoic Eon**. The Paleocene Epoch is the earliest epoch in the Tertiary Period (in the alternative, the earliest epoch in the Paleogene Period).

The Paleocene Epoch spans the time between roughly 65 million years ago (mya) and 55 mya.

The Paleocene Epoch is further subdivided into (from earliest to most recent) Danian (65 mya to 61 mya) and Thanetian (61 mya to 55 mya) stages. The **Eocene Epoch** followed the Paleocene Epoch.

The onset of the Paleocene Epoch is marked by the K-T boundary or **K-T event**, a large mass extinction. Most scientists argue that the K-T extinction resulted from—or was initiated by—a large asteroid impact in a submerged **area** off the Yucatan Peninsula of Mexico termed the Chicxulub crater. The impact caused widespread primary damage due to blast impact and firestorms. Post-impact damage to Earth's ecosystem occurred as dust, soot, and debris from the collision occluded the atmosphere to sunlight. The global darkening was sufficient to slow photosynthesis and the resulting climatic changes and widespread starvation resulted in extinction of the largest life forms with the greatest metabolic energy needs (e.g., the dinosaurs).

Other impact craters that date within the Paleocene Epoch include sites in Alberta, Canada and Marquez, Texas.

The Paleocene Epoch marks the rise of mammals as the dominant land species. During the Paleocene Epoch, climatic moderations reduced the evolutionary pressure of extreme swings in climate. Although a diversity of mammals had evolved and widely populated the changing continental landmasses long before the Paleocene Epoch, the reduction in predator species allowed land mammals to dominate and thrive—eventually setting the stage from the **evolution** of homo sapiens (humans). Pine trees appeared during the Paleocene Epoch and avian species flourished and diversified.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Evolution, evidence of; Fossil record; Fossils and fossilization; Historical geology; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleozoic Era; Pennsylvanian Period; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Supercontinents; Triassic Period

PALEOCLIMATE

Paleoclimate is the variation of the **climate** in past geologic times, prior to instrumental measurements. Paleoclimate is expressed by its parameters—paleotemperature, **precipitation** in the past, circulation, sea surface **temperature** (SST), and sea level.

The general state of the earth's climate is dependent upon the amount of energy the earth receives from the solar radiation, and the amount of energy the earth releases back to **space** in the form of infrared heat energy. Causes of climate change involve any process that can alter the global energy balance (climate forcing). Climate forcing processes can be divided into internal and external types. External processes include variations in Earth's orbit around the **Sun**. These variations change the amount of energy received from the Sun, and also cause variations of the distribution of sunlight reaching the earth's surface. Long periods of solar luminosity variations cause variations of the global climate, although lower intensity variations of luminosity may not produce detectable changes in local climate if circulation patterns modulate them. Internal processes operate within the earth's climate system, and include changes in **ocean circulation** and changes in the composition of the atmosphere. Other climate forcing processes include the impacts of large **volcanic eruptions**, and collisions with **comets** or meteorites.

Over much of the earth's geologic history, the global climate has been warmer and wetter than at present. Global temperatures early in Earth's history were 46–59°F (8–15°C) warmer than today. Polar regions were free of **ice** until periods of glaciations occurred 2,300 million years ago. For about the past one billion years, Earth's dominant climate pattern has been one of tropical regions, cool poles, and periodic **ice ages**. Most recent **glaciers** reached their maximum thickness and extent about 18,000 years ago, and then **glaciation** ended abruptly about 10,000 years ago. Since the last glacial period, sea levels changed from –132.2 yd (–120 m) during glaciation to +10.9 yd (+10 m) during interglacial maximum, due to ice sheet **melting**.

The Medieval Climatic Optimum occurred around A.D. 1000–1250. The Northern Hemisphere experienced a warm and dry climate. Most of Greenland was ice free and, therefore, was named Greenland. The Little Ice Age was a period of rapid cooling, which began after the end of the Medieval Warm period and lasted nearly until the end of the eighteenth century, reaching its peak from 1460 to 1705. During this period, the average global temperature dropped 33.8–35.6°F (1–2°C). Solar activity may have lead to climatic changes like the Little Ice Age and Medieval Climatic Optimum. The Little Ice Age coincides with a period of absence of aurora from 1460 to 1550 called the Spoerer Solar Minimum, and an absence of sunspots from 1645 to 1715 called the Maunder Minimum. The number of sunspots has been related to solar output and the emission of the radiant heat from the Sun.

Reconstructions of Paleoclimate are made by use of records of different proxies (models) of different climatic parameters. These models can be divided to quantitative, qualitative, and indirect from the point of view of the precision of the reconstruction of past climates they provide. Quantitative models are able to reconstruct the exact values of the temperature, annual precipitation or sea level, and to estimate its error. Qualitative models are able to reconstruct only their principal variations expressed through the variation of the model. Indirect models do not express variations of the climate, but of something dependent on climate through a complicated mechanism such as distribution of a certain plant type.

Speleothems (stalagmites, **stalactites** and flowstones) are producing a tremendous range of reconstructions of different types of paleoclimatic parameters, including many quantitative records. Calcite speleothems display luminescence, which is produced by calcium salts of humic and fulvic acids derived from soils above the **cave**. The luminescence of speleothems depends exponentially on the solar **insolation** (if **soil** surface is heated directly by the Sun) or on the air temperature (if the cave is covered by forest or bush). Therefore, luminescence records represent solar insolation or temperature in the past. Luminescence of many speleothems is exhibited by annual bands much like tree rings. Distance between them is a quantitative proxy of annual precipitation in the past.

Changes in the thickness of the tree rings records temperature changes if derived from temperature-sensitive tree rings, or records precipitation if derived from precipitation-sensitive tree rings. These records are modulated to some degree by the other climatic parameters.

The stable isotope records of past glaciations are preserved in glacier ice and in sea cores. These records are primarily a measure of changing volume of glacier ice. The ratio of stable isotopes in **water** is temperature dependent, and is altered whenever water undergoes a phase change. Now, the volume of land ice is relatively small, but during glacial periods, much isotopically light water was removed from **oceans** and stored in glaciers on land. This caused slight enrichment of seawater, while glacier ice had lower values of the ratio. Sea cores do not allow for a better resolution than 1,000 years, and cannot be dated precisely. Corals and speleothems often allow measurements with minor time increments. Plants and animals adapt to the climatic changes, so may be used as indirect paleoclimatic indicators. Fossil evidence provides a good record of the advancing and retreating of ice sheets, while various pollen types indicate advances and retreats of northern **forests**.

See also Insolation and total solar irradiation; Marine transgression and marine regression; Milankovitch cycles; Stalactites and stalagmites

PALEOMAGNETICS

The first ever treatise on experimental science by thirteenth century scholar Petrus Peregrinus of Marincourt dealt with **magnetism** ("Epistola de Magnete"). However, direct observations of the geomagnetic field were not recorded until the late sixteenth century, when the magnetic compass became a widespread tool for navigation. In order to understand nature and origin of Earth's **magnetic field**, however, much longer records are necessary. Paleomagnetic research draws this information from rocks that acquire a remanent magnetization upon formation.

The natural magnetization of a **rock** is parallel to the ambient magnetic field. It is carried by minute amounts of ferrimagnetic **minerals** and can be stable over geological time scales. Precise snap-shots of the past geomagnetic field are recorded by volcanic rocks, while **sedimentary rocks** retain smoothed records acquired over discrete intervals of time. Sequences of rocks can thus act like a magnetic tape, which records a piece of music. Unfortunately, the original record is usually altered secondarily through time and various **weathering** processes. Paleomagnetic methods have to be employed to remove this magnetic noise and extract a true primary magnetization.

Paleomagnetic research has shown that Earth's magnetic field has been a dipole field for more than 99.9% of Earth's history. Its shape resembles that of the field of a bar-magnet. The field lines emerge at one pole and re-enter at the other pole. The earth's magnetic field however is not caused by a huge mass of **iron** with a remanent magnetization, but its origin lies in the outer fluid core where convective motion generates the magnetic field in a self-sustaining dynamo action. This dynamic origin of the geomagnetic field is the main reason why its shape and orientation are not constant but subject to temporal variations on time scales that range from millions of years to days. Recently, for example, the dipole axis is inclined by about 11 (against the spin axis). Averaged over time spans greater than 100,000 years, the dipole axis is parallel with the earth's spin axis.

The earth's magnetic field can characteristically reverse its polarity, meaning that the magnetic poles can switch position. Other second order phenomena are termed the secular variation of Earth's magnetic field.

The temporal variations of Earth's magnetic field are widely used in geosciences. The understanding that Earth's magnetic field can truly reverse its polarity had a huge impact on our view of Earth, because the idea was crucial for the development and break-through of **plate tectonics**. This view of Earth as a dynamic system which was put forward in 1915 by German geophysicist **Alfred Wegener** (1880–1930), but was not commonly accepted until the 1960s. Only then was the cause for the characteristic pattern of the oceanic magnetic anomalies understood. They are characterized by alternating stripes of normally and inversely magnetized rocks parallel to the **mid-ocean ridges** and are caused by the continuous addition of newly formed rocks, adding new layers and pushing the rims away from the ridge, while the geomagnetic field frequently reversed.

The fact that Earth's magnetic field never fundamentally changed its shape through its history allowed paleomagnetists to investigate the movement of plates by calculating the position of the North magnetic pole from the magnetization of rocks. Assuming the earth's field is a dipole over large intervals of time, one can calculate the geographic **latitude** of a rock at the time when its remanent magnetization was acquired. By investigating rocks from subsequent time intervals, it is then possible to reconstruct the path of a plate relative to the magnetic pole, or vice versa. It allows tracking of the former distribution of plates and continents through time.

Another important application of paleomagnetism to geoscience is the opportunity to use a sequence of reversals for dating and correlating sedimentary sequences on a global scale. Magnetostratigraphy uses the globally simultaneous occurrence of dated polarity changes. This dating method can at best resolve an average of 100,000 years. However, for rocks younger than approximately 10,000 years it is possible to use calibration curves of the paleosecular variation for dating with accuracy better than a few hundred years.

Recently, another branch of paleomagnetism has become a method in its own right. Rock **magnetism** was developed as a tool to judge the reliability of the paleomagnetic record. Today it is widely used in environmental and paleoclimatic research.

See also Earth (planet); Ferromagnetic; Plate tectonics; Polar axis and tilt

PALEOZOIC ERA

In **geologic time**, the Paleozoic Era, the first era in the **Phanerozoic Eon**, covers the time between roughly 544 million years ago (mya) and until 245 mya.

The Paleozoic Era spans six geologic time periods including the **Cambrian Period** (544 to 500 mya); **Ordovician Period** (500 mya to 440 mya); Silurian (440 mya to 410 mya); Devonian (410 mya to 360 mya); and the Carboniferous Period (360 mya to 286 mya) (in many modern geological texts, especially those in the United States, the time of Carboniferous Period is covered by two alternate geologic periods, the **Mississippian Period** [360 mya to 325 mya] and the **Pennsylvanian Period** [325 mya to 286 mya]. The final geologic time period in the Paleozoic Era is the **Permian Period** (286 mya to 245 mya).

The onset of the Paleozoic Era is marked by the ‘‘Cambrian explosion,” the sudden appearance of numerous **fossils**. Although life certainly started in **Precambrian** time, The start of the Paleozoic Era marks the point at which life developed to a variety or organisms capable of leaving fossils. Although **fossilization** is difficult under any circumstances, organisms with structures such as shells have a much greater chance of leaving fossilized remains than did single celled microorganisms.

The Paleozoic Era spanned that period of geologic time during which the **evolution** of the first invertebrates, vertebrates, terrestrial (land-based) plants, bony fish, reptiles, insects, etc. took place. The end of the Paleozoic Era (approximately 245 mya) marks the largest mass extinction of species in Earth's history. During this mass extinction an estimated 90% of all Earth's marine species suddenly became extinct.

Six major continental landmasses developed during the Paleozoic Era. Although not located in their present global positions, parts of the modern continents can be traced to these landmasses. For example, continental **crust** now located in the North American continent was located near the equator during the Paleozoic Era. The forces of **plate tectonics** were active, and not only moved the continents but helped shape the continental margins though uplift and subduction. Enormous changes on sea state relative to the continents meant extensive flooding, **marine transgression**, and marine regression that added large sedimentary deposits (e.g., large **limestone** deposits). The abundance of organic life provided the start for abundant **coal** formation during the Carboniferous Period (Pennsylvanian Period and Mississippian Period).

See also Archean; Cenozoic Era; Cretaceous Period; Dating methods; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Oligocene Epoch; Paleocene Epoch; Pennsylvanian Period; Pleistocene Epoch; Pliocene Epoch; Quaternary Period; Tertiary Period; Triassic Period

PANGAEA • *see* SUPERCONTINENTS

PARALLELS • *see* LATITUDE AND LONGITUDE

PARTIAL MELTING

A process known as partial **melting** generates the molten **rock**, known as **magma**, that cools to form crystalline rocks in the earth's outer compositional layer, or its **crust**. The terms "partial melting," "partial fusion," and "anatexis" refer to processes that create a magmatic melt from a portion of a solid rock less than the whole. Because most crystalline, or igneous, rocks in the earth's crust are composed of a number of silicate **minerals** that melt at different temperatures, and of minerals with heterogeneous crystal lattices, almost all magmas are generated by partial melting.

Incongruent melting occurs over a range of temperatures; the mineral components with the lowest melting temperatures melt first, and the minerals with the highest melting temperatures melt last. Partial melts are thus enriched in the chemical components of minerals with lower melting temperatures, and the remaining unmelted portion of the rock is composed of minerals with the highest melting temperatures. There are two end member types of partial melting. In equilibrium fusion, the liquid melt continuously reacts with the residual **crystals**, changing composition until the whole rock has melted. In fractional fusion, the melted material is separated from the remaining solid rock as it is produced. Fractional fusion leads to differentiation of chemical components in the melt, and to creation of different rock types from the same magmatic source.

Earthquake wave velocities and travel paths through the earth's interior suggest that the outer core is the only fully liquid layer of our planet. However, the outer core is composed entirely of **iron**, and is not a possible source of siliceous magma. Magmatic source areas are thus confined to areas of the upper mantle and lower crust that seismic shear waves indicate to be almost entirely solid. Only a very small portion ($<$5%) of the rock in magmatic source areas is thought to be liquid. Partial melts migrate upward from their source areas to intermediate staging areas, or magma chambers, in the middle and upper crust before erupting from volcanoes, or cooling to form intrusive igneous plutons. Magmas are generated by partial melting in a number of present-day plate tectonic settings, including subduction zones, **mid-ocean ridges,** and hot spots. The granitic continental interiors, called continental shields or cratons, probably formed above ancient subduction zones, or by melting at the base of the crust during the **Precambrian** and Paleozoic Eras when more heat was escaping from the inner earth.

See also Geothermal gradient; Phase state changes

PEBBLE • *see* ROCK

PEGMATITE

A pegmatite is an intrusive igneous body of highly variable grain size that often includes coarse crystal growth. A pegmatite may be a segregation within an associated plutonic **rock** or a **dike** or vein that intrudes the surrounding **country rock**.

The composition range of pegmatites is similar to that of other intrusive **igneous rocks** and is indicated by using modifier, e.g., **granite** pegmatite or gabbro pegmatite. However, pegmatites occur most commonly in granites and the term applied alone usually refers to a granitic composition. The **mineralogy** of pegmatites can be simple or exotic. A simple granite pegmatite may contain only **quartz**, **feldspar**, and mica. More complex pegmatites are often zoned and can contain **minerals** like tourmaline, garnet, beryl, fluorite, lepidolite, spodumene, apatite, and topaz.

Pegmatites are formed as part of the cooling and crystallization process of intrusive rocks. As the parent body begins to cool, a sequential crystallization process occurs that concentrates many volatile constituents such as H_2O, boron, fluorine, chlorine, and phosphorous in a residual **magma**. In simple cases, the presence of residual **water** has simply allowed the magma to cool slowly enough to permit coarse crystal growth. More complex pegmatites are the result of the presence of numerous exotic volatiles that are eventually incorporated into rare minerals.

The most distinguishing characteristic of pegmatites is the unusually large crystal size of the minerals, which ranges from less than an inch to several feet. Single **crystals** of spodumene from the Black Hills have reached 40 ft (12 m) in length. A Maine pegmatite contained a beryl crystal 27 ft (8 m) long and 6 ft (1.8 m) wide. These exceptionally large crystals are not free-growing, rather they are intergrown with the rest of the pegmatite. However, pegmatites do produce large and beautiful individual crystals of many different minerals that are highly prized by gem and mineral collectors.

Pegmatites are also valued for the suite of rare elements that tend to be concentrated in the residual magmas. For example, beryllium is obtained from beryl, lithium from spodumene and lepidolite, and boron from tourmaline. Other rare elements obtained from pegmatites include tin, tantalum, and niobium.

See also Intrusive cooling; Pluton and plutonic bodies

PENNSYLVANIAN PERIOD

The Pennsylvanian Period lasted from 320 to 286 million years ago. During the Pennsylvanian Period, widespread swamps laid down the thick beds of dead plant material that today constitute most of the world's **coal**. The term Pennsylvanian is a U.S. coinage based on the frequency of rocks of this period in the state of Pennsylvania; internationally, the terms late Carboniferous Period or Silesian Period are preferred.

Although most artist's conceptions of the Pennsylvanian Period emphasize its prolific swamps, these were characteristic only of the equatorial regions. The

Southern Hemisphere, which was dominated by the huge continent Gondwana, underwent a series of **ice ages** during this period. These **ice** ages sequestered **water** in times of ice growth and released it in times of **melting**, causing the ocean to cyclically regress (uncover coastal lands) and transgress (cover coastal lands) around the world. Repeating sequences of sedimentary **rock** layers record these changes in sea level.

From the bottom up, a typical sequence is **sandstone**, shale, coal, **limestone**, and sandstone again. Each such unit is termed a cyclothem and was formed as follows: (1) As ice melted in Gondwana, **seas** rose globally. **Rivers** and streams deposited **sand** and gravel in the coastal lowlands as they sought new equilibrium profiles (i.e., stable altitude-vs.-distance cross-sections). This sand layer eventually became sandstone. Although the coastal zones where sandstone deposition was taking place at any one time were narrow, larges areas were blanketed by these sediments as the seas rose and coastlines swept slowly inland. (2) As the rising sea neared a given location, a lush coastal swamp developed. This deposited a thick layer of dead leaves, tree trunks, and other organic material rich in **carbon** that would eventually form coal. (3) When the sea finally submerged the swamp, a shallow marine environment appeared. The remains of shelly marine animals built up on the sea floor and eventually became limestone. (4) Ice began to build again in Gondwana, and sea levels began to drop in a new phase of regression. (5) **Erosion** of re-exposed coastal lands scraped off the topmost sediments left by the last transgression, including some of the limestone layer. (6) Ice began to melt again in Gondwana, triggering a fresh cycle of transgression.

As many as 90 cyclothems have been found in one place, one on top of the other. Each such cylothem records a complete climatic cycle like the one described above.

The first reptiles evolved during the Pennsylvanian Period. These were small (about a foot long) and outnumbered by the amphibians, which were prosperous, diverse, and achieved lengths of up to 15 ft (4.6 m). Insects also throve; dragonflies with 2.5-ft (0.76 m) wingspans were common. Over 1,000 species of Pennsylvanian cockroach have been identified, giving this period the alternative, informal title of the "age of cockroaches."

See also Archean; Cambrian Period; Carbon dating; Cenozoic Era; Continental drift theory; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Tertiary Period

PENZIAS, ARNO (1933-)

German-born American astrophysicist

Arno Penzias shared the Nobel Prize for physics in 1978 with Robert Wilson for a discovery that supported the **big bang theory** of the universe. The two radio astronomers at what was then American Telephone & Telegraph's (AT&T) Bell Telephone Laboratories were using a 20-ft (6.1-m) horn reflector antenna that year to measure the intensity of radio waves emitted by the halo of gas surrounding the galaxy. The two scientists were bothered by a persistent noise that they could not explain. At first they pinned it on two pigeons that were nesting in the antenna throat. But even after they evicted the birds, the noise continued. Eventually the scientists were able to conclude that the noise came from cosmic background, or microwave, radiation. This came to be widely considered as remnant microwave radiation from the "big bang" in which the universe was created billions of years ago. The Penzias-Wilson discovery came to be considered a major finding in astrophysics.

Arno Allan Penzias was born in Munich, Germany, to Jewish parents Karl and Justine (Eisenreich) Penzias. Hitler's campaign to wipe out the Jews of **Europe** was well underway when the family escaped in 1940. Arriving in New York, Penzias had to acclimate to a new culture and language and suffer through hard times for his family. Naturalized in 1946, he demonstrated scientific acumen at Brooklyn Technical High School and went on to obtain his B.S. at City College in New York in 1954. He married Anne Pearl Barras that same year; the union produced three children. After a two-year stint in the U.S. Army Signal Corps, Penzias obtained both his master's and Ph.D. degrees at Columbia University. He has said he chose to study physics because he asked a professor if he could make a living in the field and was told, "Well, you can do the same things engineers can do and do them better."

In 1961, Penzias was hired at Bell Labs in Holmdel, New Jersey. AT&T was a telecommunications monopoly at that time and Bell Labs was its research center, attracting the best and brightest scientific minds. In this context, Penzias demonstrated his capabilities early on. Asked to join a committee of older scientists who were trying to devise how to calculate the precise positions of communication satellites by triangulation, young Penzias suggested they use radio stars, which emit characteristic frequencies from fixed positions, as reference points. For his abilities, Penzias rose through the Bell ranks to become director of the facility's Radio Research Laboratory in 1976, and executive director of the Communications Sciences Research Division in 1979. He also took part in the pioneering Echo and Telstar communications **satellite** experiments of the 1970s.

It was astronomer George Gamow who in 1942 first calculated the conditions of **temperature** and density that would have been required for a fireball explosion or "big bang" origin of the universe 15 billion years ago. Astronomers Ralph Alpher and Robert Herman later concluded that cosmic radiation would have resulted from this event. This theory was confirmed by Penzias and Wilson. According to the theory, the background radiation resulting from the big bang would have lost energy; it would have essentially "cooled." Gamow and Alpher calculated in 1948 that the radiation should now be characteristic of a perfectly emitting body—or black body—with a temperature of about 5 Kelvin, or –268° C. The scientists said this radiation should lie in the microwave region of the spectrum; their calculations were verified by physicists Robert Dicke and P. J. E. Peebles.

Penzias's and Wilson's contribution to the issue began with a 20-ft (6.1-m) directional radio antenna, the same kind of radio antenna designed for satellite communication. Investigating an irritating noise emitted by the antenna, the two men realized in May of 1964 that what they heard was not instrumental noise but microwave radiation coming from all directions uniformly. Penzias and Wilson calculated the radiation's temperature as about 3.5 K. Dicke and Peebles, who had made the earlier calculations, got reinvolved from nearby Princeton University with a scientific explanation of the Penzias-Wilson discovery. More experiments followed, confirming that the radiation was unchanging when measured from any direction. Even after the duo received the Nobel Prize in 1978 (also awarded that year to Pyotr Kapitsa for unrelated work in physics) they continued to collaborate on research into intergalactic hydrogen, galactic radiation and interstellar abundances of the isotopes.

At the time of the federal lawsuit which led to the breakup of AT&T in 1984, Penzias, who had become vice president of research in 1981, predicted that without the operating companies as a base, Bell Labs would become "a sinking ship." That did not happen. Instead, in September of 1990, Penzias presided over the realignment of Bell Labs into a facility whose research is streamlined and oriented towards the activities of its business units.

While rearranging Bell Labs, Penzias has kept an eye on the outside world, writing *Ideas and Information: Managing in a High-Tech World* in 1989 and staying involved in the national dialogue regarding the growth of computer technology and international competition. He told *Forbes* magazine in March of 1989, "You go into Sears, the best cordless telephone you can buy is an AT&T phone. It works better. You try it."

In his personal life, Penzias, who is the proud grandfather of three, is also an avid skier, swimmer, and runner with an interest in kinetic sculpture and writing limericks. Penzias is a member of the National Academy of Sciences and the National Academy of Engineering, as well as the vice-chairman of the Committee of Concerned Scientists, devoted to political freedom for scientists internationally. He has written over 100 articles and collected more than 20 honorary degrees. Penzias holds that technology can be liberating. As he wrote in *Fortune* magazine in March of 1990: "Everybody is overstressed.... We've got to stop going to meetings and have them electronically instead.... How far away are we from realizing this dream? My guess is that by the time *Fortune* marks its 100th anniversary, a lot of this will have happened. In fact, long before I retire, I hope to have at least a multimedia terminal in my office so that I can integrate voice, data, high-definition video, conference video, document access, and shared software... who's going to do all this? I hope it's AT&T. But it could be IBM, Apple—it could be anybody." Penzias officially retired from Bell Labs in the spring of 1998, but continues to serve in a technical advisory role.

See also Cosmic microwave background radiation

PERIDOTITE

Peridotite is a dark-colored, coarse-grained igneous **rock** believed by many scientists to be the primary rock of the exterior of Earth's mantle. The rock typically forms in volcanic pipes and is forced to the surface from great depths during a volcanic eruption.

Peridotite consists of a dense **iron** and magnesia mineral called **olivine**, as well as pyroxenes and a small amount of **feldspar**. It is a pistachio-green color when fresh, but **weathering** creates iron oxides that turn it a medium brown. The iron and magnesia-rich rock is the most common host for naturally occurring diamonds. South African diamonds are obtained from a mica-rich form of peridotite called kimberlite. Periodite is also a source of valuable ores and **minerals** including chromite, platinum, nickel, and precious garnet. In rare instances, individual olivine **crystals** in periodite are large enough and pure enough to be designated a gem. The resulting gem is a semi-precious mineral called peridot.

Periodite is found worldwide, but particularly in New Zealand.

See also Gemstones; Igneous rocks; Plagioclase

PERIODIC TABLE (PREDICTING THE STRUCTURE AND PROPERTIES OF THE ELEMENTS)

An element is defined by the number of protons in the nucleus of its atoms, but its chemical reactivity is determined by the number of electrons in its outer shell—a property fundamental to the organization of the periodic table of the elements.

In the second half of the nineteenth century, data from laboratories in France, England, Germany, and Italy were assembled into a pamphlet by Stanislao Cannizzaro (1826–1910), a teacher in what is now northern Italy. In this pamphlet, Cannizzaro demonstrated a way to determine a consistent set of atomic weights, one weight for each of the elements then known. Cannizzaro distributed his pamphlet and explained his ideas at an 1860 international meeting held in Karlsruhe, Germany, that was organized to discuss new ideas about the theory of atoms. When Russian chemist and physicist Dmitri Mendeleyev (1834–1907) returned from the meeting to St. Petersburg, Russia, he pondered Cannizzaro's list of atomic weights along with an immense amount of information he had gathered about the properties of elements. Mendeleyev found that when he arranged the elements in order of increasing atomic weight, similar properties were repeated at regular intervals—they displayed periodicity. Mendeleyev used the periodic repetition of chemical and physical properties to construct a chart much like the Periodic Table we currently use.

Early in the twentieth century work initiated by Joseph John Thomson (1856–1940) in England led to the discovery of the electron and, later, the proton. In 1932, James Chadwick (1891–1974), also in England, proved the existence of the neutron in the atomic nucleus. The discovery of these elementary particles and the experimental determination of their actual weights led scientists to conclude that different atoms have different weights because they contain different numbers of protons and neutrons. However, it was not yet clear how many subatomic particles were present in any but the simplest atoms, such as hydrogen, helium and lithium.

In 1913, a third British scientist, Henry G. J. Moseley (1887–1915), determined the frequency and wavelength of x rays emitted by a large number of elements. By this time, the number of protons in the nucleus of some of the lighter elements had been determined. Moseley found the wavelength of the most energetic x ray of an element decreased systematically as the number of protons in the nucleus increased. Moseley then hypothesized the idea could be turned around: he could use the wavelengths of x rays emitted from heavier elements to determine how many protons they had in their nuclei. His work set the stage for a new interpretation of the Periodic Table.

Moseley's results led to the conclusion that the order of elements in the periodic chart was based on some fundamental principle of atomic structure. As a result of Moseley's work, scientists were convinced that the periodic nature of the properties of elements is due to differences in the numbers of subatomic particles. As each succeeding element is added across a row on the periodic chart, one proton and one electron are added. The number of neutrons added is unpredictable but can be determined from the total weight of the **atom**.

When Mendeleyev placed elements in his Periodic Table, he had all elements arranged in order of increasing relative atomic weight. However, in the modern Periodic Table, the elements are placed in order of the number of protons in the nucleus. As atomic weight determinations became more precise, discrepancies were found. The first case of a heavier element preceding a lighter one in the modern Periodic Table occurs for cobalt and nickel (58.93 and 58.69, respectively). In Mendeleyev's time, both atomic weights had been determined to be 59. Mendeleyev grouped both elements together, along with **iron** and copper. From the work of Moseley and others, the number of protons in the nuclei of the elements cobalt and nickel had been found to be 27 and 28, respectively. Therefore, the order of these elements, and the reason for their similar behavior with respect to other members of their chemical families, arises because nickel has one more proton and one more electron than cobalt.

Whereas Mendeleyev based his order of elements on mass and chemical and physical properties, the arrangement of the table now arises from the numbers of subatomic particles in the atoms of each element. The stage was now set for examining how the number of subatomic particles affects the **chemistry** of the elements. The role of the electrons in determining chemical and physical properties was obscure early in the twentieth century, but that would soon change with the pivotal work of American chemist Gilbert N. Lewis (1875–1946).

After Moseley's work, the idea that the periodic patterns in chemical reactivity might actually be due to the number of electrons and protons in atoms intrigued many chemists. Among the most notable was Lewis, then at the University of California at Berkeley. Lewis explored the relationship between the number of electrons in an atom and its chemical properties, the kinds of substances formed when elements reacted together to form compounds, and the ratios of atoms in the formulas for these compounds. Lewis concluded that chemical properties change gradually from metallic to nonmetallic until a certain "stable" number of electrons is reached.

An atom with this stable set of electrons is a very unreactive species. But if one more electron is added to this stable set of electrons, the properties and chemical reactivities of this new atom change dramatically: the element is again metallic, with the properties like elements of Group 1. Properties of subsequent elements change gradually until the next stable set of electrons is reached and another very unreactive element completes the row.

A stable number of electrons is defined as the number of electrons found in an unreactive or "noble" gas. Lewis suggested electrons occupied specific areas around the atom, called shells. The noble gas atoms have a complete octet of electrons in the outermost shell.

The observation that each element starting a new row has just one electron in a new shell opens the door to relating chemical properties to the number of electrons in a shell. Mendeleyev put elements together in a family because they had similar reactivities and properties; Lewis proposed that elements have similar properties because they have the same number of electrons in their outer shells.

Many observations of the chemical behavior of elements are consistent with this idea: the number of electrons in the outer shell of an atom (the valence electrons) determines the chemical properties of an element. Lewis extended his ideas about the importance of the number of valence electrons from the properties of elements to the bonding of atoms together to form compounds. He proposed that atoms bond with each other either by sharing electrons to form covalent bonds or by transferring electrons from one atom to another to form ionic bonds. Each atom forms stable compounds with other atoms when all atoms achieve complete shells. An atom can achieve a complete shell by sharing electrons, by giving them away completely to another atom, or by accepting electrons from another atom.

Many important compounds are formed from the elements in rows two and three in the Periodic Table. Lewis predicted these elements would form compounds in which the number of electrons about each atom would be a full shell, like the noble gases. The noble gases of rows two and three, neon or argon, each have eight electrons in the outermost valence shell. Thus, Lewis's rule has become known as the octet rule and simply states that there should be eight electrons in the outer shell of an atom in a compound. An important exception to this is hydrogen for which a full shell consists of only two electrons.

The octet rule is followed in so many compounds it is a useful guide. However, it is not a fundamental law of chemistry. Many exceptions are known, but the octet rule is a good starting point for learning how chemists view compounds and how the periodic chart can be used to make predictions about the likely existence, formulas and reactivities of chemical substances.

Elements in a vertical column of the Periodic Table typically have many properties in common. After all, Mendeleyev used similarities in properties to construct a periodic table in the first place. Because they show common characteristics, elements in a column are known as a family. Sometimes a family had one very important characteristic many chemists knew about: that characteristic became the family name. Four important chemical family names of elements still widely used are the alkali **metals**, the alkaline earths, the halogens, and the noble gases. The alkali metals are the elements in Group 1, excluding hydrogen, which is a special case. These elements—lithium, sodium, potassium, rubidium, cesium and francium—all react with **water** to give solutions that change the color of a vegetable dye from red to blue. These solutions were said to be highly alkaline or basic; hence the name alkali metals was given to these elements.

The elements of Group 2 are also metals. They combine with **oxygen** to form oxides, formerly called "earths," and these oxides produce alkaline solutions when they are dissolved in water. Hence, the elements are called alkaline earths.

The name for Group 17, the halogens, means salt former because these elements all react with metals to form salts.

The name of Group 18, the noble gases, has changed several times. These elements have been known as the rare gases, but some of them are not especially rare. In fact, argon is the third most prevalent gas in the atmosphere, making up nearly 1% of it. Helium is the second most abundant element in the universe—only hydrogen is more abundant. Another name used for the Group 18 family is the inert gases. However, Neil Bartlett, while at the University of British Columbia in Vancouver, Canada, showed over 30 years ago that several of these gases could form well-defined compounds. The members of Group 18 are now known as noble gases. They do not generally react with the common elements but do on occasion, especially if the common element is as reactive as fluorine.

Knowing the chemistry of four families of the periodic table—groups 1, 2, 17, and 18, the alkali metals, the alkaline earths, the halogens and the noble gases—enables chemists to divide the elements in the Periodic Chart into other general categories: metals and nonmetals. Metals are hard but ductile substances that conduct **electricity**. Groups 1 (excluding hydrogen) and 2 are families of metallic elements. Groups 17 and 18 contain elements with very different properties perhaps best described by what they are not—they are not metals, and hence are called nonmetals. Between Groups 1 and 2, and Groups 17 and 18 is a dividing line between these two types of elements. Most periodic charts have a heavy line cutting between **aluminum** and **silicon** and descending downward and to the right in a stair-step fashion. Elements to the left of the line are metallic; those to the right, nonmetallic. The boundary is somewhat fuzzy, however, because the properties of elements change gradually as one moves across and down the chart, and some of the elements touching that border have a blend of characteristics of metals and nonmetals; they are frequently called semi-metals or metalloids.

The elements in the center region of the table, consisting of dozens of metallic elements in Groups 3–12, including the lanthanide and actinide elements, are called the transition elements or transition metals. The other elements, Groups 1,2, and 13–18, are called the representative elements.

There is a **correlation** among the representative elements between the number of valence electrons in an atom and the tendency of the element to act as a metal, nonmetal, or metalloid. Among the representative elements, the metals are located at the left and have few valence electrons. The nonmetals are at the right and have nearly a full shell of electrons. The metalloids have an intermediate number of valence electrons.

The structure and bonding of a compound determine its chemical and physical properties. Lewis's idea of stable, filled electron shells can be used to predict what atom is bonded to what other atom in a molecule. In many cases, Lewis's octet rule is followed by taking one or more electrons from one atom to form a cation and donating the electron or electrons to another atom to form an anion. Metallic elements on the far left of the Periodic Table can lose electrons and elements on the far right can readily accept electrons. When these elements combine, ionic bonds result. An example of an ionic compound is sodium chloride. The sodium cation, Na^+, forms an ionic bond with chloride anion, Cl^-.

In covalent bonds, electrons are shared between atoms. Lewis defined a covalent bond as a union between two atoms resulting from the sharing of two electrons. Thus, a covalent bond must be considered a pair of electrons shared by two atoms. Elemental bromine, Br_2, is an example of a covalent compound. Each bromine atom has seven electrons in its outer shell and requires one electron to achieve a noble gas configuration. Each can pick up the needed electron by sharing one with the other bromine atom.

Water, the solvent of life and an important agent in many geochemical processes, is a compound formed by the combination of atoms of two nonmetallic elements, hydrogen and oxygen. Each hydrogen atom requires just one electron to fill its shell because the first shell (the number of electrons of the noble gas helium) holds only two electrons. Oxygen lacks two electrons compared with neon, the nearest noble gas. If each hydrogen can obtain one electron by sharing electrons from the oxygen atom and the oxygen atom can share one electron from each of the two hydrogen atoms, every atom will have a full shell of electrons, and two covalent bonds will be formed as a result of sharing two pairs of electrons.

One of the most important properties of an element that can be used to predict bonding characteristics is whether the element is metallic or nonmetallic.

Pure metals are typically shiny and malleable. Chemists have found metals also have common chemical properties. Metals combine in similar ways with other elements and form compounds with common characteristics. Metals combine with nonmetals to form salts. In salts, the metals tend to be cations. Salts conduct electricity well when melted or when dissolved in water or some other solvents but not when they are solid.

Most pure metals, when freshly cut to expose a new surface, are lustrous, but most lose this luster quickly by combining with oxygen, **carbon dioxide,** or hydrogen sulfide to form oxides, carbonates or sulfides. Only a few metals such as gold, silver, and copper are found pure in nature, uncombined with other elements.

Nonmetals in their elemental form are usually gases or solids. A few are shiny solids, but instead of being metallic gray they are typically black (boron, **carbon** as **graphite**), colorless (carbon as **diamond**), or highly colored (violet iodine, yellow sulfur). At room **temperature**, only one of them is a liquid (bromine).

Nonmetallic elements combine with metallic elements to form salts. In salts, the nonmetallic elements tend to be anions. Non-metals accept electrons in forming anions while metals donate electrons to form cations. This reflects a periodic property of elements: as one moves from left to right across a row on the periodic chart, on the left are the atoms of metals which tend to give up electrons relatively easily and on the right side are nonmetals which do not readily give up electrons in forming **chemical bonds**. At the start of the next row, the trend is repeated. This periodic property is referred to as electronegativity. The more readily atoms accept electrons in forming a bond, the higher their electronegativity. Metals are characterized by low electronegativities; nonmetals, by high electronegativity. Electronegativity increases across a row on the periodic chart.

Nonmetallic elements combine with each other to form compounds. Although some nonmetallic elements form solutions when mixed with other nonmetallic elements, most react with other nonmetals to form new substances. For example, at the high temperatures and pressures of an internal combustion engine, nitrogen and oxygen gases from the atmosphere react to form nitrogen oxides such as nitric oxide, NO, and nitrogen dioxide, NO_2. Nonmetallic elements form covalent bonds with each other by sharing electron pairs. This tendency to bond by sharing electrons reflects the periodic trend described above: elements on the right side of the periodic chart do not give up electrons easily when forming bonds; their electronegativity is high. They tend to either accept electrons from metals to form salts or share electrons with other nonmetals to form covalent compounds.

Metalloids typically show physical characteristics (e.g., electrical conductivity) intermediate between the metals and nonmetals. Metalloids typically act more like nonmetals than metals in their chemistry. They more often combine with nonmetals to form covalent compounds rather than salts, but they can do both. This reflects their intermediate position on the Periodic Table. They can form alloys with metals and with the other metalloids. Semiconductors are typically made from combinations of two metalloids. The minor constituent, for example germanium, is said to be "doped" into the major constituent, which is often silicon.

The boundaries between metals, nonmetals, and metalloids are arbitrary. The changes in properties as one moves from element to element on the chart are gradual.

Earth's atmosphere contains slightly more than 20% oxygen. Because oxygen is quite reactive, most elements can be found in nature as oxides. The alkali metals (Group 1) and alkaline earths (Group 2) were so named because the metallic oxides formed when the metals reacted with oxygen produced basic solutions when dissolved in water. Metallic oxides are known as basic anhydrides (anhydrous, meaning without water), because basic solutions are formed when they are added to water.

Nonmetallic elements combine with oxygen to form oxides, many of which, such as carbon dioxide, sulfur dioxide and nitrogen dioxide, are gases. When oxides of nonmetallic elements are dissolved in water, they tend to form acidic solutions or neutral solutions. Nonmetal oxides that form acidic solutions when dissolved in water are called acid anhydrides.

Transition metals react with oxygen to form a wide variety of oxides, some of which are basic and some acidic. A few transition metals are relatively unreactive and may be found in nature as pure elements.

See also Atmospheric chemistry; Atomic mass and weight; Atomic number; Atomic theory; Atoms; Chemical bonds and physical properties; Chemical elements

PERMAFROST

About 20% of Earth's surface is covered by permafrost, land that is frozen year-round. Permafrost occurs at high latitudes or at very high altitudes—anywhere the mean annual **soil temperature** is below **freezing**. About half of Canada and Russia, much of northern China, most of Greenland and Alaska, and probably all of **Antarctica** are underlain by permafrost. Areas underlain by permafrost are classified as belonging to either the continuous zone or the discontinuous zone. Permafrost occurs everywhere within the continuous zone, except under large bodies of **water**, and underlies the discontinuous zone in irregular zones of varying size. Fairbanks, Alaska, lies within the discontinuous zone, while Greenland is in the continuous zone.

The surface layer of soil in a permafrost zone may thaw during the warmer months, and the upper layer of the frozen zone is known as the permafrost table. Like the **water table**, it may rise and fall according to environmental conditions. When the surface layer thaws, it often becomes waterlogged because the meltwater can only permeate slowly, or not at all, into the frozen layer below. **Partial melting** coupled with irregular drainage leads to the creation of hummocky **topography**. Walking on permafrost is extremely difficult, because the surface is spongy, irregular, and often wet. Waterlogging of the surface layer also causes slopes in permafrost areas to be unstable and prone to failure.

Permafrost provides a stable base for construction only if the ground remains frozen. Unfortunately, construction often warms the ground, thawing the upper layers. Special care must be taken when building in permafrost regions, and structures are often elevated above the land surface on stilts. The Trans-Alaska Pipeline, along much of its length, is elevated on artificially cooled posts, and communities in permafrost regions often must place pipes and wires in above-ground conduits rather than burying them. Even roads can contribute to warming and thawing of permafrost, and are generally built atop a thick bed of gravel and dirt.

See also Creep

PERMEABILITY • *see* POROSITY AND PERMEABILITY

PERMIAN PERIOD

In **geologic time**, the Permian Period, the last period of the **Paleozoic Era**, covers the time roughly 286 million years ago (mya) until 245 mya.

The Permian Period spans two epochs. The Early Permian Epoch is the most ancient, followed by the Late Permian Epoch.

The Early Permian Epoch is divided chronologically (from the most ancient to the most recent) into the Asselian, Sakmarian, and Artinskian stages. The Late Permian Epoch is divided chronologically (from the most ancient to the most recent) into the Kungurian, Kazanian, and Tatarian stages.

In terms of paleogeography (the study of the **evolution** of the continents from **supercontinents** and the establishment of geologic features), the Permian Period was dominated by the movements of the supercontinent Pangaea, that during the Permian Period was located along the equator. Plate tectonic activity along the western border of Pangaea formed an extensive **subduction zone** that survives today as a large number of volcanoes located around the Pacific rim (i.e., the Pacific "Ring of Fire").

Differentiated by fossil remains and continental movements, the Carboniferous Period (360 mya to 286 mya) preceded the Permian Period. In many modern geological texts, especially those in the United States, the time of Carboniferous Period is covered by two alternate geologic periods, the **Mississippian Period** (360 mya to 325 mya) and the **Pennsylvanian Period** (325 mya to 286 mya). The Permian Period is followed in geologic time by start of the **Triassic Period** of the **Mesozoic Era**. The largest mass extinction in Earth's history—a catastrophic extinction of marine life—marks the close of both the Permian Period and the Paleozoic Era. Accordingly, many **fossils** dated to the Permian Period are not found in Mesozoic Era formations.

The **fossil record** indicates that more than 95% of all Permian species became extinct at the close of the Permian Period. Alternative hypotheses integrate differently the effects of loss of marine habitat due to the continued fusion of continents into Pangaea.

There were a number of major impacts from large meteorites during the Permian Period. Although no crater has been specifically identified with the impact possibly associated with the mass extinction of species, indirect evidence in the form of catastrophically fused **quartz** crystals (shocked quartz) in **area** of **Antarctica** indicates that the crater measured approximately 300 mi (450 km) in diameter. Other but smaller impact craters dating to the Permian Period have been identified in modern Florida, Quebec, and Brazil.

Because of the fusion and confluence of continental land masses in Pangaea, locations as diverse as Texas (Glass Mountains), Nova Scotia (Brule Trackways), and Germany share a similar fossil record dating to the Permian Period.

See also Archean; Cambrian Period; Cenozoic Era; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Miocene Epoch; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Phanerozoic Era; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Tertiary Period

PERUTZ, MAX (1914-2002)

English crystallographer, molecular biologist, and biochemist

Max Perutz transformed a fascination of geological processes and crystal structure into one of the fundamental techniques upon which modern molecular biology was founded. Ultimately, Perutz pioneered the use of x-ray crystallography to determine the atomic structure of proteins by combining two lines of scientific investigation—the physiology of hemoglobin and the **physics** of x-ray crystallography. His efforts resulted in his sharing the 1962 Nobel Prize in chemistry with his colleague, biochemist John Kendrew. A passionate mountaineer and skier, Perutz also applied his expertise in x-ray crystallography to the study of glacier structure and flow.

Perutz's work in deciphering the diffraction patterns of protein **crystals** opened the door for molecular biologists to study the structure and function of enzymes—specific proteins that are the catalysts for biochemical reactions in cells. Known for his impeccable laboratory skills, Perutz produced the best early pictures of protein crystals and used this ability to determine the structure of hemoglobin and the molecular mechanism by which it transports **oxygen** from the lungs to tissue.

Perutz was born in Vienna, Austria, on May 19, 1914. His parents were Hugo Perutz, a textile manufacturer, and Adele Goldschmidt Perutz. In 1932, Perutz entered the University of Vienna, where he studied organic chemistry. In 1936, Perutz landed a position as research student in the Cambridge laboratory of Desmond Bernal, who was pioneering the use of x-ray crystallography in the field of biology. Perutz, however, was disappointed again when he was assigned to research **minerals** while Bernal closely guarded his crystallography work, discussing it only with a few colleagues and never with students.

Perutz's received excellent training in the promising field of x-ray crystallography, albeit in the classical mode of mineral crystallography.

In the early 1930s, crystallography had been successfully used only in determining the structures of simple crystals of **metals**, minerals, and salts. However, proteins such as hemoglobin are thousands of times more complex in atomic structure. Physicists William Bragg and Lawrence Bragg, the only father and son to share a Nobel Prize, were pioneers of x-ray crystallography. Focusing on minerals, the Braggs found that as x rays pass through crystals, they are buffeted by atoms and emerge as groups of weaker beams which, when photographed, produce a discernible pattern of spots. The Braggs discovered that these spots were a manifestation of Fourier synthesis, a method developed in the nineteenth century by French physicist Jean Baptiste Fourier to represent regular signals as a series of sine waves. These waves reflect the distribution of atoms in the crystal.

The Braggs successfully determined the amplitude of the waves but were unable to determine their phases, which would provide more detailed information about crystal structure. Although amplitude was sufficient to guide scientists through a series of trial and error experiments for studying simple crystals, proteins were much too complex to be studied with such a haphazard and time consuming approach.

Initial attempts at applying x-ray crystallography to the study of proteins failed, and scientists soon began to wonder whether proteins in fact produce x-ray diffraction patterns. However, in 1934, Desmond Bernal and chemist Dorothy Crowfoot Hodgkin at the Cavendish laboratory in Cambridge discovered that by keeping protein crystals wet, specifically with the liquid from which they precipitated, they could be made to give sharply defined x-ray diffraction patterns. Still, it would take 23 years before scientists could construct the first model of a protein molecule.

Perutz and his family, like many other Europeans in the 1930s, tended to underestimate the seriousness of the growing Nazi regime in Germany. While Perutz himself was safe in England as Germany began to invade its neighboring countries, his parents fled from Vienna to Prague in 1938. That same summer, they again fled to Switzerland from Czechoslovakia, which would soon face the onslaught of the approaching German army. Perutz was shaken by his new classification as a refugee and the clear indication by some people that he might not be welcome in England any longer. He also realized that his father's financial support would certainly dwindle and die out.

As a result, in order to vacation in Switzerland in the summer of 1938, Perutz sought a travel grant to apply his expertise in crystallography to the study of glacier structures and flow. His research on **glaciers** involved crystallographic studies of snow transforming into **ice**, and he eventually became the first to measure the velocity distributions of a glacier, proving that glaciers flow faster at the surface and slower at the glacier's bed.

Finally, in 1940, the same year Perutz received his Ph.D., his work was put to an abrupt halt by the German invasions of Holland and Belgium. Growing increasingly wary of foreigners, the British government arrested all enemy aliens, including Perutz. Transported from camp to camp, Perutz ended up near Quebec, Canada, where many other scientists and intellectuals were imprisoned, including physicists Herman Bondi and Tom Gold. Always active, Perutz began a camp university, employing the resident academicians to teach courses in their specialties. It didn't take the British government long, however, to realize that they were wasting valuable intellectual resources and, by 1941, Perutz followed many of his colleagues back to his home in England and resumed his work with crystals.

Perutz, however, wanted to contribute to the war effort. After repeated requests, he was assigned to work on the mysterious and improbable task of developing an aircraft carrier made of ice. The goal of this project was to tow the carrier to the middle of the Atlantic Ocean, where it would serve as a stopping post for aircrafts flying from the United States to Great Britain. Although supported both by then British Prime Minister Winston Churchill and the chief of the British Royal Navy, Lord Louis Mountbatten, the ill-fated project was terminated upon the discovery that the amount of steel needed to construct and support the ice carrier would cost more than constructing it entirely of steel.

Perutz married Gisela Clara Peiser in 1942; the couple later had a son and a daughter. After the war, in 1945, Perutz was finally able to devote himself entirely to the study of hemoglobin crystals. He returned to Cambridge, and was soon joined by John Kendrew. In 1946 Perutz and Kendrew founded the Medical Research Council Unit for Molecular Biology, and Perutz became its director. Many advances in molecular biology would take place there, including the discovery of the structure of deoxyribonucleic acid (DNA).

Over the next years, Perutz refined the x-ray crystallography technology. Often bogged down by tedious mathematical calculations, the development of computers hastened the process tremendously.

By 1957, Kendrew had delineated the first protein structure through crystallography, again working with myoglobin. In 1962, Perutz and Kendrew were awarded the Nobel Prize in chemistry for their codiscoveries in x-ray crystallography and the structures of hemoglobin and myoglobin, respectively. The same year, Perutz left his post as director of the Unit for Molecular Biology and became chair of its laboratory.

Perutz was a Fellow of the Royal Society. He died on February 6, 2002.

See also Atomic theory; Crystals and crystallography

PETROLEUM

Petroleum is a term that includes a wide variety of liquid **hydrocarbons**. Many scientists also include **natural gas** in their definition of petroleum. The most familiar types of petroleum are tar, oil, and natural gas. Petroleum forms through the accumulation, burial, and transformation of organic material—such as the remains of plants and animals—by chemical reactions over long periods of time. After petroleum has been generated, it migrates upward through the earth, seeping out at the surface of the earth if it is not trapped below the surface. Petroleum accumulates when it migrates into a porous **rock** called a reservoir that has a non-porous seal or cap rock that prevents the oil from migrating farther. To fully understand how petroleum forms and accumulates requires considerable knowledge of **geology**, including **sedimentary rocks**, geological structures (faults and domes, for example), and forms of life that have been fossilized or transformed into petroleum throughout the earth's long history.

Tremendous petroleum reserves have been produced from areas all over the world. In the United States, the states of Alaska, California, Louisiana, Michigan, Oklahoma, Texas, and Wyoming are among the most important sources of petroleum. Other countries that produce great amounts of petroleum include Saudi Arabia, Iran, Iraq, Kuwait, Algeria, Libya, Nigeria, Indonesia, the former Soviet Union, Mexico, and Venezuela.

Petroleum products have been in use for many years. Primitive man might have used torches made from pieces of wood dipped in oil for lighting as early as 20,000 B.C. At around 5,000 B.C., the Chinese apparently found oil when they were digging underground. Widespread use of petroleum probably began in the Middle East by the Mesopotamians, perhaps by 3,000 B.C., and probably in other areas where oil seeps were visible at the surface of the earth. Exploration for petroleum in the United States began in 1853, when George Bissell, a lawyer, recognized the potential use of oil as a source of lamp fuel. Bissell also recognized that boring or drilling into the earth, as was done to recover salt, might provide access to greater supplies of petroleum than surface seeps. In 1857, Bissell hired Edwin Drake—often called "Colonel" Drake despite having worked as a railroad conductor—to begin drilling the first successful oil well. The well was drilled in 1859 in Titusville, Pennsylvania. Once the usefulness of oil as a fuel was widely recognized, exploration for oil increased. By 1885, oil was discovered in Sumatra, Indonesia. The famous "gusher" in the Spindletop field in eastern Texas was drilled in 1901. The discoveries of giant oil fields in the Middle East began in 1908 when the company now known as British Petroleum drilled a well in Persia (now Iran). During World Wars I and II, oil became a critical factor in the ability to successfully wage war.

Currently, petroleum is among our most important natural resources. We use gasoline, jet fuel, and diesel fuel to run cars, trucks, aircraft, ships, and other vehicles. Home heat sources include oil, natural gas, and **electricity**, which in many areas is generated by burning natural gas. Petroleum and petroleum-based chemicals are important in manufacturing plastic, wax, fertilizers, lubricants, and many other goods. Thus, petroleum is an important part of many human activities.

Petroleum, including liquid oil and natural gas, consists of substances known as hydrocarbons. Hydrocarbons, as their name suggests, comprise hydrogen and **carbon**, with small amounts of impurities such as nitrogen, **oxygen**, and sulfur. The molecules of hydrocarbons can be as simple as that of methane, which consists of a carbon **atom** surrounded by four hydrogen atoms, abbreviated as CH_4. More complex hydrocarbons, such as naphthenes, include rings of carbon atoms (and attached hydrogen atoms) linked together. Differences in the number of hydrogen and carbon atoms in molecules as well as their molecular structure (carbon atoms arranged in a ring structure, chain, or tetrahedron, for example) produce numerous types of petroleum.

Different types of petroleum can be used in different ways. Jet fuel differs from the gasoline that automobiles consume, for example. Refineries separate different petroleum products by heating petroleum to the point that heavy hydrocarbon molecules separate from lighter hydrocarbons so that each product can be used for a specific purpose. Refining reduces the waste associated with using limited supplies of more expensive petroleum products in cases in which a cheaper, more plentiful type of petroleum would suffice. Thus, tar or asphalt, the dense, nearly solid hydrocarbons, can be used for road surfaces and roofing materials, waxy substances called paraffins can be used to make candles and other products, and less dense, liquid hydrocarbons can be used for engine **fuels**.

Petroleum is typically found beneath the surface of the earth in accumulations known as fields. Fields can contain oil, gas, tar, **water**, and other substances, but oil, gas, and water are the most common. In order for a field to form, there must be some sort of structure to trap the petroleum, a seal on the trap that prohibits leakage of the petroleum, and a reservoir rock that has adequate pore space, or void space, to hold the petroleum. To find these features together in an **area** in which petroleum has been generated by chemical reactions affecting organic remains requires many coincidences of timing of natural processes.

Petroleum generation occurs over long periods of time—millions of years. In order for petroleum generation to occur, organic matter such as dead plants or animals must accumulate in large quantities. The organic matter can be deposited along with sediments and later buried as more sediments accumulate on top. The sediments and organic material that accumulate are called source rock. After burial, chemical activity in the absence of oxygen allows the organic material in the source rock to change into petroleum without the organic matter simply rotting. A good petroleum source rock is a sedimentary rock such as shale or **limestone** that contains between 1% and 5% organic carbon. Rich source rocks occur in many environments, including **lakes**, deep areas of the **seas** and **oceans**, and swamps. The source rocks must be buried deep enough below the surface of the earth to heat up the organic material, but not so deep that the rocks metamorphose or that the organic material changes to **graphite** or materials other than hydrocarbons. Temperatures less than 302°F (150°C) are typical for petroleum generation.

Once a source rock generates and expels petroleum, the petroleum migrates from the source rock to a rock that can store the petroleum. A rock capable of storing petroleum in its pore spaces, the void spaces between the grains of sediment in a rock, is known as a reservoir rock. Rocks that have sufficient pore space through which petroleum can move include **sandstone**, limestone, and rocks that have many fractures. A good reservoir rock might have pore space that exceeds 30% of the rock volume. Poor quality reservoir rocks have less than 10% void space capable of storing petroleum. Rocks that lack pore space tend to lack **permeability**, the property of rock that allows fluid to pass through the pore spaces of the rock. With very few pores, it is not likely that the pores are connected and less likely that fluid will flow through the rock than in a rock with larger or more abundant pore spaces. Highly porous rocks tend to have better permeability because the greater number of pores and larger pore sizes tend to allow fluids to move through the reservoir more easily. The property of permeability is critical to producing petroleum: if fluids can not migrate through a reservoir rock to a petroleum production

Barrels of motor oil are one product of the distillation, or cracking, of crude oil. © ***Vince Streano/Corbis. Reproduced by permission.***

well, the well will not produce much petroleum and the money spent to drill the well has been wasted.

In order for a reservoir to contain petroleum, the reservoir must be shaped and sealed like a container. Good petroleum reservoirs are sealed by a less porous and permeable rock known as a seal or cap rock. The seal prevents the petroleum from migrating further. Rocks like shale and salt provide excellent seals for reservoir rocks because they do not allow fluids to pass through them easily. Seal-forming rocks tend to be made of small particles of sediment that fit closely together so that pore spaces are small and poorly connected. The permeability of a seal must be virtually zero in order to retain petroleum in a reservoir rock for millions to hundreds of millions of years, the time span between formation of petroleum to the discovery and production of many petroleum fields. Likewise, the seal must not be subject to forces within the earth that might cause fractures or other breaks in the seal to form.

Reservoir rocks and seals work together to form a trap for petroleum. Typical traps for petroleum include hills shaped similar to upside-down bowls below the surface of the earth, known as anticlines, or traps formed by faults. Abrupt changes in rock type can form good traps, such as sandstone deposits next to shale deposits, especially if a **sand** deposit is encased in a rock that is sufficiently rich in organic matter to act as a petroleum source and endowed with the properties of a good seal.

An important aspect of the formation of petroleum accumulations is timing. The reservoir must have been deposited prior to petroleum migrating from the source rock to the reservoir rock. The seal and trap must have been developed prior to petroleum accumulating in the reservoir, or else the petroleum would have migrated farther. The source rock must have been exposed to the appropriate **temperature** and pressure conditions over long periods of time to change the organic matter to petroleum. The necessary coincidence of several conditions is difficult to achieve in nature.

Petroleum exploration and production activities are performed primarily by geologists, geophysicists, and engineers. Geologists look for areas of the earth where sediments accumulate. They then examine the area of interest more closely to determine whether or not source rocks and reservoir rocks exist there. They examine the rocks at the surface of the earth and information from wells drilled in the area. Geologists also examine **satellite** images of large or remote areas to evaluate the rocks more quickly.

Geophysicists examine seismic data, data derived from recording waves of energy introduced into the rock layers of the earth through dynamite explosions or other means, to determine the shape of the rock layers beneath the surface and whether or not traps such as faults or anticlines exist.

Once the geologist or geophysicist has gathered evidence of potential for a petroleum accumulation, called a prospect, an engineer assists in determining how to drill a well or multiple wells to assess the prospect. Drilling a well to explore for petroleum can cost as little as $100,000 and as much as $30,000,000 or more, depending on how deep the well must be drilled, what types of rocks are present, and how remote the well location is. Thus, the scientists must evaluate how much the well might cost, how big the prospect might be, and how likely the scientific predictions are to be correct. In general, approximately 15% of exploration wells are successful.

Once a successful exploration well has been drilled, the oil and/or gas flow are pumped to the surface of the earth through the well. At the surface, the petroleum either moves through a pipeline or is stored in a tank or on a ship until it can be sold.

Estimates of the amount of recoverable oil and natural gas in the United States are 113 billion barrels of oil and 1,074 trillion cubic feet of natural gas. Worldwide estimates of recoverable oil and natural gas are 1 trillion barrels of oil and 5 quadrillion cubic feet of natural gas. These worldwide reserves are expected to supply 45 years of fuel at current production rates with expected increases in demand. However, such estimates do not take into account reserves added through new discoveries or through the development of new technology that would allow more oil and natural gas to be recovered from existing oil and natural gas fields.

Daily consumption of oil in the United States exceeds 17 million barrels of oil per day, of which approximately 7 million barrels are in the form of gasoline for vehicles. Over half the petroleum consumed in the United States is imported from other countries. (Assuming oil costs $20 per barrel and 8.5 million barrels per day are imported, over one billion dollars per week are spent on oil imports). While the United States has tremendous reserves of petroleum, the undiscovered fields that remain tend to be smaller than the fields currently producing petroleum outside of the United States. Thus, less expensive foreign reserves are imported to the United States. When foreign petroleum increases in price, more exploration occurs in the United States as it becomes more profitable to drill wells in order to exploit smaller reservoirs.

Current research in petroleum includes many different activities. Within companies that explore for and produce petroleum, scientists and engineers try to determine where they should explore for petroleum, how they might recover more petroleum from a given field, and what types of tools can be lowered into wells in order to enhance our understanding of whether or not that individual well might have penetrated an oil or gas field. They also examine fundamental aspects of how the earth behaves, such as how rocks form and what forms of life have existed at various times in the earth's history. The United States Geological Survey continues to evaluate petroleum reserves and new technology to produce oil and gas. The federal government operates several facilities called Strategic Petroleum Reserves that store large quantities of petroleum for use in times of supply crisis.

Petroleum exploration specialists are using a type of geophysical data known as three-dimensional seismic data to study the structures and rock types below the surface of the earth in order to determine where exploration wells might successfully produce petroleum. Geochemists are assessing the results of studies of the **chemistry** of the surface of the earth and whether or not these results can improve the predictions of scientists prior to drilling expensive exploratory wells.

Significant recent discoveries of petroleum have been made in many areas of the world: Algeria, Brazil, China, Egypt, Indonesia, the Ivory Coast, Malaysia, Papua New Guinea, Thailand, the United Kingdom, and Vietnam, among others. In the United States, the **Gulf of Mexico**, Gulf Coast states, California, and Alaska continue to attract the interest of explorers.

See also Fossils and fossilization; Fuels and fuel chemistry; Geochemistry; Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration; Sedimentation; Syncline and anticline

PETROLEUM DETECTION

Four main issues control the occurrence and distribution of oil and gas: source, reservoir, seal, and trap.

A source is a fine-grained **rock** unit containing sufficient organic matter so that when it is heated and/or placed under pressure (maturation), **hydrocarbons** are generated. If the organic matter is of marine algal origin, then the source rock is most likely to generate oil under optimum maturation conditions, whereas rocks dominated by land plant matter will tend to create gaseous hydrocarbons. The hydrocarbons are of lower **gravity** than the surrounding **groundwater** and, therefore, move away from and generally upwards (migration) from the source rock until they are trapped in a reservoir.

A reservoir is a rock unit that acts as a storage device for the hydrocarbons that migrate from the source rock. Hydrocarbons are retained within the reservoir because these rocks contain numerous pores (essentially microscopic-sized holes) between the mineral grains making up the fabric of the reservoir. In good quality reservoirs the **porosity** is frequently over 20% of the rock volume. However, the pores need to be interlinked in such a manner that the fluids can move into (and out of, if we are to exploit the oil and gas) the reservoirs over geological time. This is known as **permeability**. There are two main rock types that make up the giant reservoirs around the world—sandstones that are made up of **sand** grains (**quartz** and **feldspar** in the majority) and carbonates that are made up of organically created calcium carbonate grains (corals, algae and shells) or mud. In order to stop the upward movement of hydrocarbons and constrain them to one zone of the subsurface (trap), there must be a barrier to prevent fluid migration. Generally this mechanism or seal consists of rocks that are impermeable to fluid flow. The most effective of these seals are mudstones or shales, very fine-grained rocks containing abundant **clay minerals**. Occasionally the impermeable layers are dense **igneous rocks** and in rare situations, there may be significant rock and fluid pressure differences in a region that prevents fluid flow and acts as a seal.

Equally important is the presence of a trapping mechanism. They are either of structural form where the reservoir rock unit is contorted to produce a zone where fluids naturally accumulate against a seal, or of stratigraphic nature where a reservoir rock unit changes laterally into an impermeable unit reflecting changes in depositional environment along one bed. Upwarping of rocks (anticlinal **folds**) are particularly good at trapping hydrocarbons along with faults where permeable titled reservoir strata are moved up against impermeable strata.

Detection of hydrocarbons in the subsurface during exploration takes a number of forms: direct identification of hydrocarbons at the surface, direct hydrocarbon indicators (DHI) in the subsurface, and indirect indicators both at the surface and in the subsurface. Traditionally, oil exploration was primarily conducted by recognizing seeps of hydrocarbons at the surface. The Chinese, for example, used oil (mostly bitumen) obtained from seeps for use in medication, waterproofing, and warfare several thousand years ago. The ancient Chinese frequently dug shallow pits or horizontal tunnels at the seep locations in order to recover the oil. In Baku, Azerbaijan, there are still gas and oil seeps that are permanently alight and have been used to light caravanserai since the times of Marco Polo and the Silk route. With the dawning of the modern era in Oil Creek, Pennsylvania, Colonel Edwin Drake drilled the first well to intentionally look for oil in the subsurface in 1859. Again, this was based on direct identification of seeped hydrocarbons at the surface. Initially the oil was used to provide kerosene for lamps but the later invention of automobiles drove up demand and ushered in modern methods of oil exploration.

Around the turn of the century and up until the 1950s, the main exploration tool used for finding oil was the use of intensive and detailed geological mapping. This was frequently in terrain that was remote and inhospitable. The early pioneers working their way through the jungles of Burma, the deserts of Iraq, or the mountains of Iran, would conduct detailed evaluations of the nature and distribution of rock units that could represent potential reservoirs, seals, and source units as well as frequency, orientation, and geological history of folds or faults that could act as traps for the migrating hydrocarbons. If all four of the features required for oil or gas to be created and trapped can be recognized in a region, then a variety of play concepts can be generated. Detailed local study might identify a suitable target (prospect) and then a shallow well would be drilled to test the features.

One of the most important recent discoveries in **petroleum** studies has been **plate tectonics**. Not only has this revolutionized the earth sciences, but also it has provided a conceptual setting for oil exploration. The movement of plates around the surface of Earth creates large-scale depressions into which substantial quantities of sediments eroded from the surrounding high ground may accumulate. These accumulations can exceed thicknesses of several thousand kilometers and are referred to as sedimentary basins. By comparison of basins around the world and by analogy to existing producing hydrocarbon regions, an exploration team can say which basins are worth looking at in more detail. Then explorationists will spend time ensuring that within the basin there are present all the key elements that control the presence of hydrocarbons. Assuming that all the needed features are present, the team would agree that the basin contained a viable petroleum system and prospect generation can proceed.

In modern exploration programs, the mapping of gravity and magnetic anomalies would normally be the first two methods to be applied to a new basin or region being evaluated. These techniques would be used to identify large-scale changes in the structure of the basement and sedimentary basins together with major differences in rock density such as the influx of dense igneous rocks or light salt into a sedimentary sequence. These techniques are large scale, can be applied over both land and **water** and can even be collected remotely from plane or **satellite**.

At the same time, **remote sensing** of onshore areas initially based on large scale photogeological surveys and, after the 1970s, by satellite imaging, can identify areas with anticlinal and faulted structural features, seeps or salt domes frequently associated with oil occurrences. Offshore remote sensing of the sea surface can lead to the identification of slicks associated with the seepage of oil (both natural and man-made) into the water column. A coarse two-dimensional grid of seismic data is then collected to obtain a picture of the subsurface in the **area** to be targeted. Seismic data collection involves the generation of a seismic wave using an energy source such as an air-gun in water, dynamite in drill holes inland or a truck with a plate that is thumped down onto the road/soil surface (vibroseis). The wave travels through the earth's rock layers and reflects back off key surfaces. The time taken for the waves to be received back at the surface along with their strength is recorded via geophones and displayed on a seismic section. Processing the two-dimensional seismic sections using highly sophisticated software reveals the detailed structure of the subsurface and in certain circumstances shows the presence of direct hydrocarbon indicators such as bright spots associated with gas/water differences. Primarily, though, seismic is used to indicate the nature of folded and faulted structures that could prove to be suitable hydrocarbon traps. These are frequently referred to as leads.

The objective of seismic acquisition and processing is to acoustically image the subsurface in a geologically accurate manner with as high resolution as possible. For a detailed analysis of a small area representing a field or prospect, a high density and calibrated three-dimensional seismic is collected. Modern technology also allows scientists to accurately map changes in fluid movements through time (repeat multiple 3-D seismic surveys, known as 4-D seismic) and this technique is now particularly important in monitoring production performance of the reservoir.

Ultimately, however, the only way of confirming the presence or absence of hydrocarbons at depth is by drilling the prospect. In certain areas of the world where drilling is cheap and the subsurface has been explored extensively, such as certain onshore basins of the United States, drilling is commonly preferred to extensive and expensive seismic acquisition. Wells are then analyzed using electric, sonic, and radioactive logging techniques that measure characteristics of the rocks and fluids. These methods can identify the presence of oil and gas, which can then be tested to see if they occur at commercially viable production levels. On the other hand, at a cost of over ten million dollars per offshore exploration well, the oil companies are also likely to employ the sophisticated battery of direct and indirect detection techniques first before resorting to drilling in these areas.

See also Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration

PETROLEUM, ECONOMIC USES OF

From the dawn of time up through the late 1800s, economic development depended largely on the strength of man, animal, and to limited use **water**, **wind**, and steam. Economic conditions progressed from clans of primitive gatherers to reasonably advanced agricultural societies. As the industrialized age was in its early stages, the primary sources of energy were wood, **coal**, and whale oil. The environmental impact of utilizing these energy sources was extreme and growing worse.

Petroleum has been a known commodity through areas of natural seepage to the surface since early man, but was generally inaccessible to the masses. Its full potential had not yet begun to be realized. Population growth placed great economic stress on traditional **fuels**, and rising prices encouraged the search for alternatives.

In 1854, Canadian Abraham Gesner discovered an alternative to whale oil for use in lighting lamps by distilling kerosene from coal and oil. Edwin Laurentine Drake drilled the first successful oil well in 1859 in Titusville, Pennsylvania, and created an industry that would go on to make petroleum the most significant single economic factor to date over the entire history of the world. Industries not possible without petroleum and its derivatives now dominate world economy.

Petroleum exists within the substrata of the earth in a number of forms depending on the hydrocarbon source, maturation process, elemental exposure, and the **temperature** and pressure of the reservoir. Crude oil is the most common form of petroleum and may range in specific **gravity** from being as light as 0.73 to being as heavy as over 1.07. Under standard surface conditions, the lightest crude oil will be a thin liquid of a brown or brownish-blue/green color, while the heaviest will be a black solid tar-like substance. The corresponding physical properties and chemical compositions also vary widely and determine which products may be derived from each specific crude oil and what refining processes will be most efficient in doing so.

Early refining techniques yielded barely 4.5 gal (17 L) of gasoline per standard barrel of crude oil (42 gal, or 159 L) and much of the remaining raw materials were underutilized. Continuing technical advances in a wide range of chemical processes, however, has significantly improved the efficient conversion of a barrel of crude oil to an ever-widening range of products that contribute to almost every facet of modern life. The typical barrel now yields 21 gal (80 L) of gasoline, 3 gal (11 L) of jet fuel, 9 gal (34 L) of distillates and petrochemical feedstock, 4 gal (15 L) of lubricants, and 3 gal (11 L) of heavy residue.

Gasoline is the primary fuel used to power internal combustion engines widely used in vehicles and machines. Jet fuel is used to power the extremely powerful engines that drive high performance aircraft.

Distillates are used to produce lower grade fuels such as kerosene for use as a heating fuel and diesel fuel for use in powerful vehicles such as trucks, ships and industrial machinery. Other even lower grade fuels are used to provide energy to industrial processes not requiring the same combustion quality required by higher speed engines. Distillates also yield a wide variety of waxes that are turned into products used for lining milk cartons, as water repellant coatings, cosmetics, electrical insulators, sealants, medicinal tablet coatings, crayons, candles, and many other everyday items.

Petrochemical feedstock is processed into supplying an ever growing assortment of products such as anti-freeze, bases for paints, cleaning agents, detergents, dyes, explosives, fertilizers, industrial resins, plastics, synthetic fibers (nylon, polyester, rayon), synthetic rubber, solvents, thinners, and varnishes. Though all of these products have helped improve how people live, the impact of plastics is among the most consequential petroleum products in the civilized world.

Lubricants help overcome friction and are produced in an assortment of greases and oils used to lubricate moving parts in machinery; pull electrical wire through insulating conduit; lubricate sewing needles, sliding doors, heavy loads, and surgical medical equipment; and to reduce drag on surf boards as they pass through water.

Finally, the heavy residue left over is in the form of tar, pitch, and asphalt. Tar and pitch were first discovered by early man laying in surface seeps or pools, having been cooked off from oil deposits deep within Earth's surface and was used to seal boats and preserve wood. Today, more refined forms of these heavy residues are used in much the same way and also to pave roadways.

See also Fuels and fuel chemistry; Geochemistry; Petroleum detection; Petroleum extraction; Petroleum, history of exploration

PETROLEUM EXTRACTION

After an exploration effort has successfully discovered **petroleum** within an acceptable range of reserve potential, the challenge becomes how to best optimize extraction of recoverable reserves in a manner yielding an acceptable economic return on total cash expenditures required over the life of the project. Surface and subsurface conditions of a discovery have considerable impact on the extraction process, its related costs, and ultimate project success or failure. Technical success is one thing; economic success is another. Real world experience has shown that economic success is by far the more difficult accomplishment, as it is dependent on factors well beyond the means of science and technology.

Petroleum reserves exist as oil or gas within trapping sections of reservoir **rock** formed by structural and or stratigraphic geologic features. **Water** is the predominant fluid found in the **permeability** and **porosity** of subsurface strata within the earth's **crust**. Both oil and gas have a low specific **gravity** relative to water and will thus, float through the more porous sections of reservoir rock from their source **area** to the surface unless restrained by a trap. Typically, reservoir rock consists of **sand**, **sandstone**, **limestone**, or **dolomite**. A trap is a reservoir that is overlain by a dense cap rock or a zone of very low or no porosity that restrains migrating hydrocarbon. Petroleum bearing reservoirs can exist from surface seeps to subsurface depths over 4 mi (6.4 km) below sea level. Reservoirs vary from being quite small to covering several thousands of acres, and range in thickness from a few inches to hundreds of feet or more.

The process of evaluating how to best optimize extraction of recoverable reserves begins with a development plan. The development plan considers all available geologic and engineering data to make an initial estimate of reserves in-place, to project recovery efficiencies and optimal recoverable reserve levels under various producing scenarios, and to evaluate development plan alternatives. Development alternatives will include the number of wells to be drilled and completed for production or injection, well spacing and pattern, processing facility requirements, product transportation options, cost projections, project schedules, depletion plans, operational programs, and logistics and economic studies.

In general, petroleum is extracted by drilling wells from an appropriate surface configuration into the hydrocarbon-bearing reservoir or reservoirs. Wells are designed to contain and control all fluid flow at all times throughout drilling and producing operations. The number of wells required is dependent on a combination of technical and economic factors used to determine the most likely range of recoverable reserves relative to a range of potential investment alternatives.

The complexity and cost of drilling wells and installing all necessary equipment to produce reserves can vary significantly. The development of an onshore shallow gas reservoir located among other established fields may be comparatively low cost and nominally complex. A deep oil or gas reservoir located in 4,000+ ft (1,219+ m) of water depth located miles away from other existing producing fields will push the limits of emerging technology at extreme costs. Individual wells in deepwater can and have cost in excess of 50 million dollars to drill, complete, and connect to a producing system. Onshore developments may permit the phasing of facility investments as wells are drilled and production established to minimize economic risk. However, offshore projects may require 65% or more of the total planned investments to be made before production start up, and impose significant economic risk.

Once production begins, the performance of each well and reservoir is monitored and a variety of engineering techniques are used to progressively refine reserve recovery estimates over the producing life of the field. The total recoverable reserves are not known with complete certainty until the field has produced to depletion or its economic limit and abandonment.

The ultimate recovery of original in-place volumes may be as high as one-third for oil and 80% or more for gas. There are three phases of recovering reserves. Primary recovery occurs as wells produce because of natural energy from expansion of gas and water within the producing formation, pushing fluids into the well bore and lifting them to the surface. Secondary recovery occurs as artificial energy is applied to lift fluids to surface. This may be accomplished by injecting gas down a hole to lift fluids to the surface, installation of a subsurface pump, or injecting gas or water into the formation itself. Secondary recovery is done when well, reservoir, facility, and economic conditions permit. Tertiary recovery occurs when means of increasing fluid mobility in oil reservoirs within the reservoir are introduced in addition to secondary techniques. This may be accomplished by introducing additional heat into the formation to lower the viscosity (thin the oil) and improve its ability to flow to the well bore. Heat may be introduced by either injecting steam in a "steam flood" or injecting **oxygen** to enable the ignition and combustion of oil within the reservoir in a "fire flood." Such methods are undertaken only in a few unique situations where technical, environmental and economic conditions permit. Most gas reserves are produced during the primary recovery phase. Secondary recovery has significantly contributed to increasing oil recoveries.

Many technical assumptions become better understood and more certain with the evaluation of performance data over the producing life of a field. One of the most critical assumptions, however, remains uncertain and holds project success at risk to the very end—the oil and gas price forecast.

See also Petroleum, detection; Petroleum, economic uses of; Petroleum, history of exploration

PETROLEUM, HISTORY OF EXPLORATION

Exploration for **hydrocarbons** (oil, gas, and condensate) is commonly acknowledged to have begun with the discovery at Oil Creek, Pennsylvania, by "Colonel" Edwin Drake in 1859. However, this was only the start of the modern global era of technology-driven advances in exploration. Traditionally, oil exploration was conducted by recognizing seeps of hydrocarbons at the surface. The Chinese, for example, used oil (mostly bitumen) obtained from seeps in medication, waterproofing, and warfare several thousand years ago. They frequently dug shallow pits or horizontal tunnels at seep locations but also, as early as 200 B.C., drilled down as much as 3,500 ft (1,067 m) using rudimentary bamboo poles (making Drake's 69.5 ft [21.2 m] over 2,000 years later seem puny by comparison). In Baku, Azerbaijan, there are still gas and oil seeps that are permanently on fire and have been used to light caravanserai since the times of Marco Polo and the Silk Route. Similarly, seeps were recognized and exploited in the Caucasus (Groznyy region of Chechnya), Ploesti in Romania, Digboi in Assam, Sanga Sanga in eastern Borneo and Talara in Peru.

The first oil well, drilled by Colonel Edwin Drake near Titusville, Pennsylvania. ***AP/Wide World. Reproduced by permission.***

Even Drake's well, the first to intentionally look for oil in the subsurface, was based on direct identification of seeped hydrocarbons at the surface. Initially, the oil produced was used to provide kerosene for lamps, but the later invention of automobiles drove up demand and ushered in modern methods of oil exploration. In fact, most oil until the turn of the twentieth century was in one form or another related to seep identification. However, one theory developed during this time was to have a profound impact on exploration. In the mid 1800s, William Logan, first Director of the Geological Survey of Canada, recognized oil seeps associated with the crests of convex-upward folded rocks and employed a geologist, Thomas Hunt, to formalize his "anticlinal theory." This idea, however, was only recognized as a viable tool for exploration when Spindletop was discovered on the Gulf Coast of Texas in 1901. For the next 30 years, the anticlinal theory dominated exploration, to the extent that many believed that there were no other types of hydrocarbon accumulation. As a result, geologists became critical to understand the structural configurations of **rock** sequences which, when combined with seep occurrences, proved to be the keys to discovering the main oil-producing provinces of the United States, Mexico, and Venezuela. For a period of time before World War I, Oklahoma, Texas, and California were the World's leading production areas.

Around the turn of the century and up until the 1950s, the main exploration tool used for finding oil was the use of intensive and detailed geological mapping. This was frequently in terrain that was remote and inhospitable. The early pioneers working their way through the jungles of Burmah, India (Burmah oil company, now part of British **Petroleum**), and Borneo (Shell), the deserts of Iraq or the mountains of Iran (the Anglo-Persian Oil Company that became British Petroleum), would conduct detailed evaluations of the nature and distribution of rock units. These rock units represented potential reservoirs, seals, and source units, as well as frequency, orientation, and geological history of **folds** or faults that could act as traps for the migrating hydrocarbons.

It took until the 1920s for explorers to realize that hydrocarbons could occur in situations where no **anticline** was preserved. For example, it was noted as far back as 1880 that oil was trapped in the Venango Sands of Pennsylvania, not in the form of an anticlinal structure, but by the lithologies occurring in a moving palaeoshoreline. In fact, oil trapped by **stratigraphy** was discovered more often by chance rather than design even until the 1970s. By the 1920s, mapping of surface features was complimented by the development of seismic refraction, **gravity**, and magnetic geophysical methods. In particular, gravity and seismic methods proved effective in locating oil trapped against buried salt domes in the onshore **Gulf of Mexico**. At this time, another significant advance in exploration of the subsurface took place with the application of geophysical techniques by the Schlumberger brothers to measuring properties of rocks and fluids encountered whilst drilling for hydrocarbons. In France in 1927, they initially measured the resistivity of the rocks in shallow wells (drilled primarily for **water** distribution), but later went on to add other electric, sonic, and radioactive logging tools. It is now even possible to log **porosity**, **permeability**, **mineralogy**, and fluids and image the structures and rock types downhole. Ultimately, these developments have been one of the main reasons why Schlumberger has become one of the largest electronics companies in the world.

Aerial **remote sensing** for features favored for hydrocarbon accumulation became an important and effective technique, particularly in areas of sparse vegetation cover following World War II when low-cost, rapid reconnaissance of large areas became feasible. Large-scale features such as faults and folds could be identified and targeted for detailed seismic acquisition. In the 1970s, this capability was improved dramatically by the use of **satellite** remote sensing technologies (LANDSAT).

From the 1940s to the 1960s, there were important developments in the understanding of the controls on lateral and vertical variations within reservoir sequences. In particular, the new discipline of sedimentology used modern depositional analogues from around the world to understand the nature, distribution and controls over ancient reservoir sequences. There was also much interest generated over the discovery of carbonate oil-bearing reservoirs in West Texas and Canada (Leduc Reef), and recognition that modern intertidal carbonate-evaporite sequences in the UAE had equivalents in ancient reservoirs. These developments lead to the discovery of many super giant carbonate oil fields in the United States (Yates Field), Mexico (Posa Rica), Middle East (Kirkuk), and Russia (a number of Siberian oil fields).

Other tools such as **geochemistry**, developed during this period, have helped to quantify the level of maturity and the nature and distribution of source potential in a region. Micropalaeontology was developed in Tertiary Basins such as Trinidad and the Caucasus for horizon identification and **correlation** using planktonic foraminefera, but spread rapidly to the United States Gulf Coast. Now, geochemistry and biostratigraphy, including palynology (the study of spores and other organic matter), have become standard tools in the explorationist's armory.

Also beginning in the 1970s, there was a significant advance in the power and reduction in size and cost of computers that has lead directly to a dramatic increase in the ability of geophysicists to acquire, process, and interpret large quantities of seismic data. Initially, this was in the form of 2-D reflection seismic onshore, but this trend has continued to the present day and now oil companies regularly undertake, mostly offshore, 3-D seismic surveys and even 4-D field surveys. Three-dimensional surveys are repeated over the same **area** every few years to monitor fluid movement within reservoirs and thereby optimally manage hydrocarbon recovery. Highly complex three-dimensional models of the subsurface can be displayed on sophisticated workstations or in the form of a fully enclosed room where staff can be totally immersed in the data using special glasses and can "walk through" the reservoirs to, for example, choose the optimal location and direction of wells.

Exploration for oil and gas has progressed dramatically in the last 30 years, driven forward by the ever-increasing power and capabilities of the computer. As a result, it now takes only a fraction of the time required 20 years ago to find and develop oil fields. However, technology in itself does not find oil or gas fields; it frequently requires a flash of inspiration that is the mark of a true explorer to discover some of the major new exploration plays in such areas as Equatorial Guinea, Angola, Nigeria, Trinidad, the Gulf of Mexico, and the northern Canadian Rockies.

See also Fuels and fuel chemistry; Petroleum detection; Petroleum, economic uses of; Petroleum extraction

PETROLEUM MICROBIOLOGY

Microorganisms play an important role in the formation, recovery, and uses of **petroleum**. Petroleum is broadly considered to encompass both oil and **natural gas**. The microorganisms of concern include bacteria and fungi.

Much of the experimental underpinnings of petroleum microbiology are a result of the pioneering work of Claude ZoBell. Beginning in the 1930s and extending through the late 1970s, ZoBell's research established that bacteria are important in a number of petroleum related processes.

Bacterial degradation can consume organic compounds in the ground, which is a prerequisite to the formation of petroleum.

Some bacteria can be used to improve the recovery of petroleum. For example, experiments have shown that starved bacteria, which become very small, can be pumped down into an oilfield, and then resuscitated. The resuscitated bacteria plug up the very porous areas of the oilfield. When **water** is subsequently pumped down into the field, the water will be forced to penetrate into less porous areas, and can push oil from those regions out into spaces where the oil can be pumped to the surface.

Alternatively, the flow of oil can be promoted by the use of chemicals that are known as surfactants. A variety of bacteria produce surfactants, which act to reduce the surface tension of oil-water mixtures, leading to the easier movement of the more viscous oil portion.

In a reverse application, extra-bacterial polymers, such as glycocalyx and xanthan gum, have been used to make water more gel-like. When this gel is injected down into an oil formation, the gel pushes the oil ahead of it.

A third **area** of bacterial involvement involves the modification of petroleum **hydrocarbons**, either before or after collection of the petroleum. Finally, bacteria have proved very useful in the remediation of sites that are contaminated with petroleum or petroleum by-products.

The bioremediation aspect of petroleum microbiology has grown in importance in the latter decades of the twentieth century. In the 1980s, the massive spill of unprocessed (crude) oil off the coast of Alaska from the tanker Exxon *Valdez* demonstrated the usefulness of bacteria in the degradation of oil that was contaminating both seawater and land. Since then, researchers have identified many species of bacteria and fungi that are capable of utilizing the hydrocarbon compounds that comprise oil. The hydrocarbons can be broken down by bacteria to yield **carbon dioxide** and water. Furthermore, the bacteria often act as a consortium, with the degradation waste products generated by one microorganism being used as a food source by another bacterium, and so on.

A vibrant industry has been spawned around the use of bacteria as petroleum remediation agents and enhancers of oil recovery. The use of bacteria involves more than just applying an unspecified bacterial population to the spill or the oilfield. Rather, the bacterial population that will be effective depends on factors such as the nature of the contaminant, **pH**, **temperature**, and even the size of the spaces between the rocks (i.e., **permeability**) in the oilfield.

Not all petroleum microbiology is concerned with the beneficial aspects of microorganisms. Bacteria such as *Desulfovibrio hydrocarbonoclasticus* utilize sulfate in the generation of energy. While originally proposed as a means of improving the recovery of oil, the activity of such sulfate reducing bacteria (SRBs) actually causes the formation of acidic compounds that “sour” the petroleum formation. SRBs can also contribute to dissolution of pipeline linings that lead to the burst pipelines, and plug the spaces in the **rock** through which the oil normally would flow on its way to the surface. The growth of bacteria in oil pipelines is such a problem that the lines must regularly be scoured clean in a process that is termed “pigging,” in order to prevent pipeline blowouts. Indeed, the formation of acid-generating adherent populations of bacteria has been shown to be capable of dissolving through a steel pipeline up to one-half an inch thick within a year.

See also Biosphere; Fuels and fuel chemistry; Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration

PH

pH is a measure of the acidity or alkalinity of a solution. The variability of pH can have a dramatic effect on geochemical processes (e.g., **weathering** processes).

The pH scale was developed by Danish chemist Søren Peter Lauritz Sørensen (1868–1939) in 1909 and is generally presented as ranging from 0 to 14, although there are no theoretical limits on the range of the scale (there are substances with negative pH’s and with pH’s greater than 14, although for most substances the range of 0–14 suffices). A solution with a pH of less than 7 is acidic and a solution with a pH of greater than 7 is basic (alkaline). The midpoint of the scale, 7, is neutral. The lower the pH of a solution, the more acidic the solution is and the higher the pH, the more basic it is. Mathematically, the potential hydronium ion concentration (pH) is equal to the negative logarithm of the hydronium ion concentration: $pH = -\log [H_30^+]$, where H_3O^+ represents the hydronium ion.

Essentially, the hydronium ion can be thought of as a **water** molecule with a proton attached. The square brackets indicate the concentration of, in moles per liter. Thus, $[H_3O^+]$ indicates the concentration of hydronium ions in moles per liter.

The hydronium ion is an important participant in the chemical reactions that take place in aqueous (water, H_20) solutions.

Through a process termed self-ionization, a small number of water molecules in pure water dissociate (separate) in a reversible reaction to form a positively charged H^+ ion and a negatively charged OH^- ion. In aqueous solution, as one water molecule dissociates, another is nearby to pick up the loose, positively charged, hydrogen proton to form a positively charged hydronium ion (H_3O^+).

Water molecules have the ability to attract protons and form hydronium ions because water is a polar molecule. **Oxygen** is more electronegative than hydrogen. As a result, the electrons in each of water’s two oxygen-hydrogen bonds to spend more time near the oxygen **atom**. Because the electrons are not shared equally—and because the bond angles of the water molecule do not cancel out this imbalance—the oxygen atom carries a partial negative charge that can attract positively charged protons donated by other molecules.

In a sample of pure water, the concentration of hydronium ions is equal to 1×10^{-7} moles per liter (0.0000001 M). The water molecule that lost the hydrogen proton—but that kept the hydrogen electron—becomes a negatively charged hydroxide ion (OH^-).

The equilibrium (balance) between hydronium and hydroxide ions that results from self-ionization of water can be disturbed if other substances that can donate protons are put into solution with water.

The pH of solutions may be measured electronically with a pH meter (better pH meters can measure to 0.001 pH units) or by using acid base indicators, chemicals that change color in solutions of different pH.

See also Acid rain; Geochemistry; Weathering and weathering series

PHANEROZOIC EON

The Phanerozoic Eon represents **geologic time** from the end of **Precambrian** time, approximately 544 to 570 million years ago (mya), until the present day. As such, the Phanerozoic Eon includes the **Paleozoic Era**, the **Mesozoic Era**, and the current **Cenozoic Era**. The Phanerozoic Eon and constituent eras are then further divided into 12 geologic periods.

The Phanerozoic Eon derives its name from *phaneros*, meaning visible or evident, and *zoon*, meaning life. Although early life existed in Precambrian time—including prokaryotes (e.g., bacteria) and eukaryotes (organisms with a true nucleus containing DNA)—the onset of the Phanerozoic Eon marks the start of complex life (e.g., invertebrates) found in the **Cambrian Period**.

In terms of the **fossil record**, the Phanerozoic Eon represents not the **origin of life**, but of life capable of leaving extensive fossil remains (e.g., organisms with shells, etc.). Fossilization refers to the series of postmortem (after death) changes that lead to replacement of **minerals** in the original hard parts (shell, skeleton, teeth, horn, scale) with different minerals, a process known as remineralization. Infrequently, soft parts may also be mineralized and preserved as **fossils**. Fossils of soft bodied Precambrian time fossils have been found but, as expected, they are rare and present an incomplete evolutionary record.

See also Archean; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Pennsylvanian Period; Pleistocene Epoch; Pliocene Epoch; Proterozoic Era; Quaternary Period; Silurian Period; Tertiary Period; Triassic Period

PHASE STATE CHANGES

A change of state occurs when matter is converted from one physical state to another. For example, when **water** is heated, it changes from a liquid to a gas—when cooled water will eventually freeze into a solid: **ice**. A change of state is usually accompanied by a change in **temperature** and/or pressure.

Matter commonly exists in one of three forms, or states: solid, liquid, or gas. One fundamental way in which these three states differ from each other is the energy of the particles of which they are made. The particles in a solid contain relatively little energy and move slowly. The particles in a liquid are at a higher energy level and move more rapidly. The particles in a gas are at an even higher energy level and move most rapidly.

The state in which matter occurs can be changed by changing the energy state of the matter or the system surrounding matter that has the capacity to come into equilibrium with that system. When water is heated, molecules begin to move more rapidly. Eventually, they are moving fast enough to change to the gaseous, or vapor, state. The term vapor is used to describe the gaseous state of a substance that is normally a liquid at room temperature.

Imagine a block of ice at 14°F (–10°C). The molecules of water in the ice are vibrating in a crystalline array. As heat is added to the ice, the molecules begin vibrate more rapidly. At some point, they vibrate rapidly enough to break the lattice array and move freely in a liquid state. The point at which this occurs is the **melting** point. The melting point is the temperature at which a solid changes to a liquid. The melting point of ice is 32°F (0°C).

If additional heat is added to the liquid water, water molecules move even faster. The increase in speed with which they move is measured as an increase in temperature. The temperature of the liquid water increases from 32°F (0°C) to 212°F (100°C). At a temperature of 212°F (100°C), the water molecules are moving fast enough to change to a vapor, called steam. The temperature at which a liquid changes to a gas is called its boiling point. The temperature is a function of **atmospheric pressure**. The lower the pressure (e.g., lower pressures found at altitude) the lower the boiling point.

If the steam formed in this process is heated further, its temperature continues to increase.

Changes of state occur also when a material is cooled. Suppose the steam in this example is cooled below 212°F (100°C). When that happens, the water reverts to a liquid. The steam is said to condense to a liquid. The **condensation** point is the temperature at which a gas or vapor changes to a liquid. It is the same as the boiling point of the liquid.

Under the proper conditions, at some point, the liquid cools sufficiently to change to a solid. At this point, the liquid becomes frozen. The **freezing** point of a liquid is the temperature at which the liquid changes to a solid. The freezing point is the same as the melting point of the solid.

Some materials behave differently from water when they are heated. They may pass directly from the solid state to the gaseous state. Iodine is an example. When solid iodine is heated, it does not melt. Instead, it changes directly into a vapor. Substances that behave in this way are said to sublime. The sublimation point of a substance is the temperature at which it changes directly from a solid to a vapor.

Dry ice (solid CO_2), which rapidly undergoes sublimation from solid to vapor at room temperatures, is often used to create **fog** on stage and movie sets. A white, opaque solid, it is

Dry ice, or frozen carbon dioxide, goes from a solid state to a gaseous state at normal pressure and temperature, unlike water ice, which goes from a solid state to a liquid state. This process is called sublimation. Please note that dry ice should never be touched with bare hands, as it is cold enough to cause severe damage to exposed skin. Proper precautions should always be taken when handling dry ice. *R. Fowell. National Audubon Society Collection/Photo Researchers, Inc. Reproduced by permission.*

also widely used as a cryogenic agent in industry to reduce bacteria growth and maintain low temperatures. At atmospheric pressures found on Earth, dry ice undergoes sublimation at –109.3°F (–78.5°C). Special care must be taken when working with dry ice to avoid frostbite. In addition, dry ice must be used in a well-ventilated environment because, as it undergoes sublimation, dry ice will reduce the percentage of available **oxygen**.

See also Atmospheric chemistry; Atoms; Hydrothermal processes; Ice heaving and ice wedging; Rate factors in geologic processes

PHYLLITE

Phyllite is an intermediate-grade, foliated **metamorphic rock** type that resembles its sedimentary parent **rock**, shale, and its lower-grade metamorphic counterpart, **slate**. Like slate, phyllite can be distinguished from shale by its foliation, called slaty cleavage, and its brittleness, or fissility. Both slate and phyllite are generally dark-colored; their most common color is dark gray-blue, but dark red and green varieties also exist. Unlike slate, phyllite has a characteristic glossy sheen, its foliation is usually slightly contorted, and it rarely retains traces of the original sedimentary **bedding**. Phyllite also lacks the large, visible mica **crystals** and high-grade index **minerals** diagnostic of **schist**, its higher-grade metamorphic cousin.

Heating and compression of clay-rich, bedded **sedimentary rocks** called shales creates a series of rock types of increasing metamorphic grade: slate, phyllite, schist, and **gneiss**. During **metamorphism** of shales, and occasionally volcanic ash layers, metamorphism transforms platy **clay** minerals into small sheets of mica. As the intensity of heating and compression, the so-called metamorphic grade, increases, the mica sheets align themselves perpendicular to the direction of stress, and they grow larger. In phyllite, the crystals of sheet-silicate minerals like chlorite, biotite, and muscovite are large enough to give the rock its distinctive satin sheen and slaty cleavage, but not large enough to be visible to the unaided eye. The amount of heat and pressure required to transform shale to phyllite is generally sufficient to destroy any original sedimentary layering. Additional metamorphism transforms phyllite to schist; all the original clay and small mica crystals transform into large mica crystals, any remaining organic material is destroyed, and high-grade metamorphic index minerals like garnet and staurolite grow in the micaceous matrix.

Slates and phyllites typically form along the edges of regional metamorphic belts where clay-rich, marine sedimentary rocks have been caught between colliding continental plates, or scraped off the seafloor into an accretionary wedge above a **subduction zone**. Slates and phyllites may also form in sedimentary basins where marine muds have been extremely deeply buried. The assemblage of minerals usually present in phyllite is referred to as greenschist facies, and includes chlorite, muscovite, sodium-rich **plagioclase feldspar**, and a small amount of **quartz**. Greenschist metamorphism of shales requires moderate amounts of both heating and compression, consistent with the conditions present in accretionary wedges, shallow continental fold belts, and very deep sedimentary basins.

See also Greenstone belt

PHYLLOSILICATES

Phyllosilicates are a group of minerals that are fundamentally composed of extended flat sheets of linked silicon-oxygen tetrahedra. Included in the phyllosilicate family are micas and clays. The name is derived from the Greek word *phyllos*, meaning leaf. As the name implies, phyllosilicates often display a platy or flaky crystal habit or perfect planar cleavage.

The phyllosilicate structure consists of sheets of hydrated SiO_4 rings (they are hydrated because there is one hydroxyl ion [OH^-] in the middle of each ring) and an octahedral sheet consisting of AlO or MgO. The simplest phyllosilicate is a sole octahedral layer: brucite in the case of MgO, gibbsite if the octahedral layer is AlO. However, most phyllosilicates are composed of interlocking tetrahedral and octahedral layers combined in the ratio of 1:1 or 2:1. One tetrahedral layer linked to one octahedral layer yields the 1:1 structure. This forms kaolinite when an AlO octahedral layer is used, antigorite if the octahedral layer consists of MgO. Other **clay** minerals such as talc and pyrophyllite are composed of a 2:1 structure: two tetrahedral layers sandwiching one octahedral layer. In both structures, 1:1 and 2:1, a weak residual interlayer charge exists. This interlayer charge is the source of the van der Waals forces that hold each interlocked layer to one another. These weak interlayer bonds are easily broken and allow the sheets to slip, resulting in the low hardness and greasy feel that is typical of clays.

Other phyllosilicate minerals are derived from further complications of the interlocking sheet system. For example, the micas are formed when atoms of **aluminum** substitute for **silicon** in the tetrahedral layer. Because these two elements carry different charges, the net charge of the 2:1 layers is increased. The result is an interlayer bond that is stronger than a van der Waals forces and produces the perfect planar cleavage and slightly higher hardness of micas.

See also Clay; Phyllite

PHYSICAL GEOGRAPHY

Physical geography is a scientific discipline that addresses the distribution of natural features and processes within a spatial, or geographical, reference frame. This subdiscipline of geography is an interdisciplinary amalgam of such diverse subjects as **geology**, ecology, environmental science, computer science, and aerospace engineering. When examined, the narrow definition of physical geography as the study and creation of physical maps expands into a broad array of topics from **satellite remote sensing** to computer-aided mapping known as geographic information systems (**GIS**), to the study of surficial geological processes. The basic work of physical geology lies in determining how natural phenomena are spatially ordered, and in illuminating these geographic patterns using maps and images; the fundamental question behind physical geographic studies is why these patterns exist in nature.

The history of physical geography spans nearly four thousand years. Archeologists have discovered maps created by ancient Chinese, Phoenician, and Egyptian explorers, including a Babylonian map carved in a **clay** tablet dated at about 2300 B.C. Aristotle (384–322 B.C.) suggested that the earth is a sphere based on his observations of lunar cycles. Eratosthenes (circa 276–194 B.C.) accurately calculated the circumference of the earth using a geometric proof. **Ptolemy** (circa A.D. 100–170) developed a number of map **projection** schemes, as well as the coordinate system using **latitude and longitude**. Most of these early Greek and Roman geographical insights were forgotten during the Middle Ages (600–1400), especially in **Europe**. In fact, the idea of a spherical Earth did not resurface until the Renaissance when European navigators, including Christopher Columbus, **Ferdinand Magellan**, and Sir Francis Drake, explored the **oceans** and the Americas. Increasingly detailed physical and cultural geographic studies accompanied the rapid population growth, European colonization, and exploration of the American frontier that took place from the late 1700s the early 1900s.

Physical geography underwent a quantitative revolution beginning in the 1950s, when geographic investigations became more scientifically rigorous. This revolution continues today with ever-improving geographical methods and tools like satellite-aided navigation using the Global Positioning System (**GPS**), and images of the earth collected from **space**. Another change in the science of physical geography since the 1950s has been an increasing focus on the ways that humans affect their natural environment. Precise geographical information that documents or explains anthropogenic changes in the natural world is valuable to decision-makers across the ideological spectrum, from environmentalists, to government resource managers, to insurance actuaries.

See also History of exploration I (Ancient and classical); History of exploration II (Age of exploration); Mapping techniques; Projections

PHYSICS

Physics and **astronomy**, from which all other sciences derive their foundation, are attempts to provide a rational explanation for the structure and workings of the Universe. The creation of the earliest civilizations and of mankind's religious beliefs was profoundly influenced by the movements of the **Sun**, **Moon**, and stars across the sky. As our most ancient ancestors instinctively sought to fashion tools through which they gained mechanical advantage beyond the strength of their limbs, they also sought to understand the mechanisms and patterns of the natural world. From this quest for understanding evolved the science of physics. Although these ancient civilizations were not mathematically sophisticated by contemporary standards, their early attempts at physics set mankind on the road toward the quantification of nature.

In Ancient Greece, in a natural world largely explained by the whim of gods, the earliest scientists and philosophers of record dared to offer explanations of the natural world based on their observations and reasoning. Pythagoras (582–500 B.C.) argued about the nature of numbers, Leucippus (c. 440 B.C.), Democritus (c. 420 B.C.), and Epicurus (342–270 B.C.) asserted matter was composed of extremely small particles called atoms.

Many of the most cherished arguments of ancient science ultimately proved erroneous. For example, in Aristotle's (384–322 B.C.) physics, for example, a moving body of any mass had to be in contact with a "mover," and for all things there had to be a "prime mover." Errant models of the universe made by **Ptolemy** (c. A.D. 100–170) were destined to dominate the Western intellectual tradition for more than a millennium. Midst these misguided concepts, however, were brilliant insights into natural phenomena. More then 1700 years before the Copernican revolution, Aristarchus of Samos (310–230 B.C.) proposed that the earth rotated around the Sun and **Eratosthenes Of Cyrene** (276–194 B.C.), while working at


Researchers at the Fermi National Accelerator Laboratory, or Fermilab, are expanding the limits of our knowledge of particle physics. © *Michael S. Yamashita/Corbis. Reproduced by permission.*

the great library at Alexandria, deduced a reasonable estimate of the circumference of the earth.

Until the collapse of the Western Roman civilization there were constant refinements to physical concepts of matter and form. Yet, for all its glory and technological achievements, the science of ancient Greece and Rome was essentially nothing more than a branch of philosophy. Experimentation would wait almost another two thousand years for injecting its vigor into science. Although there were technological advances and more progress in civilization than commonly credited, during the Dark and Medieval Ages in **Europe** science slumbered. In other parts of the world, however, Arab scientists preserved the classical arguments as they developed accurate astronomical instruments and compiled new works on mathematics and optics.

At the start of the Renaissance in Western Europe, the invention of the printing press and a rediscovery of classical mathematics provided a foundation for the rise of empiricism during the subsequent Scientific Revolution. Early in the sixteenth century, Polish astronomer Nicolaus Copernicus's (1473–1543) reassertion of heliocentric theory sparked an intense interest in broad quantification of nature that eventually allowed German astronomer and mathematician **Johannes Kepler** (1571–1630) to develop laws of planetary motion. In addition to his fundamental astronomical discoveries, Italian astronomer and physicist **Galileo Galilei** (1564–1642) made concerted studies of the motion of bodies that subsequently inspired seventeenth century English physicist and mathematician Sir Isaac Newton's (1642–1727) development of the laws of motion and gravitation in his influential 1687 work, *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy).*

Following the *Principia*, scientists embraced empiricism during an Age of Enlightenment. Practical advances spurred by the beginning of an industrial revolution resulted in technological advances and increasingly sophisticated instrumentation that allowed scientists to make exquisite and delicate calculations regarding physical phenomena. Concurrent advances in mathematics, allowed development of sophisticated and quantifiable models of nature. More tantalizingly for physicists, many of these mathematical insights ultimately pointed toward a physical reality not necessarily limited to three dimensions and not necessarily absolute in time and **space**.

Nineteenth century experimentation culminated in the formulation of Scottish physicist James Clerk Maxwell's (1831–1879) unification of concepts regarding **electricity**, **magnetism**, and light in his four famous equations describing electromagnetic waves.

During the first half of the twentieth century, these insights found full expression in the advancement of quantum and **relativity theory**. Scientists, mathematicians, and philosophers united to examine and explain the innermost workings of the universe—both on the scale of the very small subatomic world and on the grandest of cosmic scales.

By the dawn of the twentieth century more than two centuries had elapsed since Newton's *Principia* set forth the foundations of classical physics. In 1905, in one grand and sweeping Special Theory of Relativity, German-American physicist **Albert Einstein** (1879–1955) provided an explanation for seemingly conflicting and counter-intuitive experimental determinations of the constancy of the speed of light, length contraction, time dilation, and mass enlargements. A scant decade later, Einstein once again revolutionized concepts of space, time and **gravity** with his General Theory of Relativity.

Prior to Einstein's revelations, German physicist Maxwell Planck (1858–1947) proposed that atoms absorb or emit electromagnetic radiation in discrete units of energy termed quanta. Although Planck's quantum concept seemed counter-intuitive to well-established Newtonian physics, quantum mechanics accurately described the relationships between energy and matter on atomic and subatomic scale and provided a unifying basis to explain the properties of the elements.

Concepts regarding the stability of matter also proved ripe for revolution. Far from the initial assumption of the indivisibility of atoms, advancements in the discovery and understanding of **radioactivity** culminated in renewed quest to find the most elemental and fundamental particles of nature. In 1913, Danish physicist **Niels Bohr** (1885–1962) published a model of the hydrogen **atom** that, by incorporating **quantum theory**, dramatically improved existing classical Copernican-like atomic models. The quantum leaps of electrons between orbits proposed by the **Bohr model** accounted for Planck's observations and also explained many important properties of the photoelectric effect described by Einstein.

More mathematically complex atomic models were to follow based on the work of the French physicist Louis Victor de Broglie (1892–1987), Austrian physicist **Erwin Schrödinger** (1887–1961), German physicist Max Born (1882–1970) and English physicist P.A.M Dirac (1902–1984). More than simple refinements of the Bohr model, however, these scientists made fundamental advances in defining the properties of matter—especially the wave nature of subatomic particles. By 1950, the articulation of the elementary constituents of atoms grew dramatically in numbers and complexity and matter itself was ultimately to be understood as a synthesis of wave and particle properties.

Against a maddeningly complex backdrop of politics and fanaticism that resulted in two World Wars within the first half of the twentieth century, science knowledge and skill became more than a strategic advantage. The deliberate misuse of science scattered poisonous gases across World War I battlefields at the same time that advances in physical science (e.g., x-ray diagnostics) provided new ways to save lives. The dark abyss of WWII gave birth to the atomic age. In one blinding flash, the Manhattan Project created the most terrifying of weapons that could—in an blinding flash—forever change the course of history for all peoples of the earth.

The insights of relativity theory and quantum theory also stretched the methodology of science. No longer would science be mainly exercise in inductively applying the results of experimental data. Experimentation, instead of being only a genesis for theory, became a testing ground to test the apparent truths unveiled by increasingly mathematical models of the universe. Moreover, with the formulation of quantum mechanics, physical phenomena could no longer be explained in terms of deterministic causality, that is, as a result of at least a theoretically measurable chain causes and effects. Instead, physical phenomena were described as the result of fundamentally statistical, unreadable, indeterminant (unpredictable) processes.

The development of quantum theory, especially the delineation of Planck's constant and the articulation of the Heisenburg uncertainty principle carried profound philosophical implications regarding limits on knowledge. Modern cosmological theory (i.e., theories regarding the nature and formation of the universe) provided insight into the evolutionary stages of stars (e.g., neutron stars, pulsars, black holes, etc.) that carried with it an understanding of nucleosythesis (the formation of elements) that forever linked mankind to the lives of the very stars that had once sparked the intellectual journey towards an understanding of nature based upon physical laws.

With specific regard to **geology**, the twentieth century development of geophysics and advances in sensing technology made possible the revolutionary development of plate tectonic theory.

See also Earth Science; History of exploration I (Ancient and classical); History of exploration II (Age of exploration); History of exploration III (Modern era); History of geoscience: Women in the history of geoscience; History of manned space exploration

PICCARD, JACQUES ERNEST-JEAN (1922-)

Swiss oceanic engineer, physicist, and economist

Jacques Piccard is a Swiss oceanic engineer best noted for making the deepest ocean dive (with Lt. Don Walsh) in the bathyscaph *Trieste*, a submersible vessel he helped build with his father, Auguste Piccard.

Jacques Ernest-Jean Piccard was born in Brussels, Belgium in 1922, where his Swiss-born father taught at the city's university. He attended the École Nouvelle de Suisse Romande in Lausanne, Switzerland, and in 1943, enrolled at the University of Geneva where he studied economics, history and **physics**. Piccard put his education on hold for a year in 1944 to serve with the French First Army. Upon leaving the service, he resumed studies and went on to receive his licentiate in 1946.

In the 1950s, Piccard joined his father in designing new and improved deep ships or "bathyscaphes." Their 50-ft (15-m) long navigable diving vessel, the *Trieste*, consisted of a heavier-than-water steel cabin that could resist sea pressure and a float filled with gasoline to provide lift. On August 1, 1953, the pair launched the *Trieste* to a depth of 10,168 ft (3,099 m) off the coast of Ponza, Italy.

Jacques Piccard then took the idea to the United States government in 1956; two years later the U.S. Navy acquired the *Trieste* and redesigned the cabin so the vehicle could descend to deeper **ocean trenches**. Subsequently, the Navy asked Piccard to serve as their consultant.

It was during this time that Piccard performed what many believe to be his most noteworthy accomplishment. On January 23, 1960, Piccard, along with U.S. Navy Lieutenant Don Walsh, made a dive in the *Trieste* to the deepest known point on Earth. The team descended 35,810 ft (10,916 m) in **area** known as the Challenger Deep in Pacific's Mariana Trench. Piccard and Walsh sat in a 6-ft-diameter (1.8-m) steel capsule at the base of the ship while the vessel made the nearly five-hour dive to the ocean floor. Just shy of 7 mi (11 km), the dive set a new submarine depth record. In the decades since the feat, no one has come within 10,000 ft (3,048 m) of Piccard and Walsh's record.

In later years, the *Trieste* helped locate the sunken nuclear submarine U.S.S. *Thresher*, and documented information on another sunken sub, U.S.S. *Scorpion*. The original *Trieste* now sits in the Navy Museum in Washington, D.C.

In the 1960s, Piccard continued to work with his father and designed the first tourist submarine. The mesoscaphe, as they called it, was an underwater observation vehicle capable of carrying 40 tourists.

For most of his life, Piccard has continued the oceanographic work inspired by his father. He has served as a consultant for a number of private deep-sea research organizations, including the Grumman Aircraft Engineering Corporation. His son, Bertrand, has kept the Piccard spirit of adventure alive, but by traveling up instead of down. In 1999, Bertrand Piccard and his teammate, Brian Jones, became the first to circumnavigate the globe in a hot-air balloon.

See also Deep sea exploration

PILLOW LAVA • *see* LAVA

PIPE, VOLCANIC

The central conduit by which **magma** rises through a **volcano** is termed a volcanic pipe. A volcanic pipe may be anywhere from a few yards to about 0.5 mi (0.8 km) in width. When a volcano ceases to erupt, its pipe generally becomes plugged by a column of solidified magma mixed with angular fragments of **rock** ripped from the walls of the pipe. This solid column is also termed a pipe (or neck, or plug). **Erosion** may strip the cone from around such a plug to create a free-standing pillar.

A pipe forms when magma from a deep reservoir drills or blasts upward. One mechanism by which this is occurs involves convection, that is, vertical circulation driven by the density difference between hotter and cooler magmas: hotter magma rises, cooler magma sinks. Magma in a narrow vertical pipe quickly loses heat to surrounding rocks, and the magma thus cooled sinks along the sides of the pipe while hot, fresh magma ascends in the pipe's center. This central fountain erodes chunks of rock from the pipe's roof, extending the pipe upward. These chunks are transported by down-convecting magma to the reservoir below, where they are melted down and assimilated. This process enables a pipe to rise through many miles of rock without having to push rocks aside.

Magma containing large amounts of dissolved gas can widen a pipe explosively by a mechanism resembling that of an erupting **geyser**. If magma reaches the surface via a relatively narrow pipe and encounters substantial **groundwater**, a large steam explosion may occur: the pipe explodes at the top. This suddenly removes weight from the magma column in the pipe, reducing the pressure on magma deeper down. Gas dissolved in this deeper magma boils out explosively, blowing still more material out of the top of the pipe and further reducing the pressure on magma still deeper down. A series of explosive eruptions can thus propagate downward to great depth. The rubble-choked pipe left after such an eruption is termed a diatreme.

If an ascending pipe full of hot magma encounters a layer of groundwater but conditions are not right for a downward-propagating explosion, a simple steam explosion at the surface may result that excavates a large, shallow crater or maar. Maars closely resemble meteor impact craters because they do not rise above the terrain surrounding them.

See also Crater, volcanic; Fissure; Magma chamber; Volcanic eruptions; Volcanic vent

PLAGIOCLASE

Plagioclase is a form of the mineral **feldspar**. All feldspars are **crystals** of **aluminum**, **oxygen**, and **silicon**, plus a major additive. In the case of plagioclase, the additive is calcium, sodium, or a blend of both. Miscellaneous impurities may also be present.

Like other feldspars, plagioclases have a vitreous (glassy) luster, are translucent or transparent, and are typically pink, gray, or white in color. Plagioclase cleaves along two planes that intersect at about 86 degrees, hence its name (from the Greek *plagio*, slanted, and *clase*, breaking). About 29% of the earth's **crust** consists of plagioclase.

There are two pure or extreme forms of plagioclase. Albite ($NaAlSi_3O_8$) contains sodium but no calcium, and anorthite $CaAl_2Si_2O_8$ contains calcium but no sodium. Many plagioclases consist of both **minerals** microscopically blended to form what is termed a solid solution. Plagioclase blends can occur along a linear continuum from albite to anorthite, intermediate minerals being mixtures of both. Plagioclase with 10–30% anorthite is defined as oligoclase; 30–50%, andesine; 50–70%, labradorite; and 70–90%, bytownite. The remainder in all cases is albite. A plagioclase with less than 10% anorthite is classified simply as albite, while one with less than 10% albite is classified simply as anorthite. A continuous, evenly represented series of plagioclases is not actually found in the field; oligoclases with anorthite percentages in the low twenties are most common, while some other points on the continuum are scarcely represented at all. The plagioclases are difficult to distinguish from each other without laboratory tests.

Many plagioclases are zoned. Zoning is the concentric or onion-skin structuring of an individual plagioclase crystal (often only a few millimeters long) with layers of varying sodium–calcium content. For example, a plagioclase crystal may consist of an andesine core (30–50% anorthite) surrounded by thin shells or zones of labradorite (50–70% anorthite) alternating with zones of andesine. Zoning records the chemical and thermal environment in which a plagioclase crystal formed.

Plagioclases are used for ceramics and glassmaking, and several gemstone varieties exist.

See also Bowen's reaction series; Mineralogy

PLANCK, MAX (1858-1947)

German physicist

Max Planck is best known as one of the founders of the **quantum theory** of **physics**. As a result of his research on heat radiation, Planck concluded that energy can sometimes be described as consisting of discrete units, later given the name *quanta*. This discovery was important because it made possible, for the first time, the use of matter-related concepts in an analysis of phenomena involving energy. Planck also made important contributions in the fields of thermodynamics, relativity, and the philosophy of science. He was awarded the 1918 Nobel Prize in physics for his discovery of the quantum effect.

Max Karl Ernst Ludwig Planck was born in Kiel, Germany. His parents were Johann Julius Wilhelm von Planck, originally of Göttingen, and Emma Patzig, of Griefswald. Max was the couple’s fourth child.

Johann von Planck was descended from a long line of lawyers, clergyman, and public servants and was himself Professor of Civil Law at the University of Kiel. Young Max began school in Kiel, but moved at the age of nine with his family to Münich. There he attended the Königliche Maximillian Gymnasium until his graduation in 1874.

Planck entered the University of Münich in 1874 with plans to major in mathematics. He soon changed his mind, however, when he realized that he was more interested in practical problems of the natural world than in the abstract concepts of pure mathematics. Although his course work at Münich emphasized the practical and experimental aspects of physics, Planck eventually found himself drawn to the investigation of theoretical problems. It was, biographer Hans Kango points out in *Dictionary of Scientific Biography*, “the only time in [his] life when he carried out experiments.”

Planck’s tenure at Münich was interrupted by illness in 1875. After a long period of recovery, he transferred to the University of Berlin for two semesters in 1877 and 1878. At Berlin, he studied under a number of notable physicists, including Hermann Helmholtz and Gustav Kirchhoff. By the fall of 1878, Planck was healthy enough to return to Münich and his studies. In October of that year, he passed the state examination for higher-level teaching in math and physics. He taught briefly at his alma mater, the Maximillian Gymnasium, before devoting his efforts full time to preparing for his doctoral dissertation. He presented that dissertation on the second law of thermodynamics in early 1879 and was granted a Ph.D. by the University of Münich in July of that year.

Planck’s earliest field of research involved thermodynamics, an **area** of physics dealing with heat energy. He was very much influenced by the work of Rudolf Clausius, whose work he studied by himself while in Berlin. He discussed and analyzed some of Clausius’s concepts in his own doctoral dissertation. Between 1880 and 1892, Planck carried out a systematic study of thermodynamic principles, especially as they related to chemical phenomena such as osmotic pressure, boiling and **freezing** points of solutions, and the dissociation of gases. He brought together the papers published during this period in his first major book, *Vorlesungen über Thermodynamik*, published in 1897.

During the early part of this period, Planck held the position of Privat-Dozent at the University of Münich. In 1885, he received his first university appointment as extraordinary professor at the University of Kiel. His annual salary of 2,000 marks was enough to allow him to live comfortably and to marry his childhood sweetheart from Münich, Marie Merck. They eventually had three children.

Planck’s research on thermodynamics at Kiel soon earned him recognition within the scientific field. Thus, when Kirchhoff died in 1887, Planck was considered a worthy successor to his former teacher at the University of Berlin. Planck was appointed to the position of assistant professor at Berlin in 1888 and assumed his new post the following spring. In addition to his regular appointment at the university, Planck was also chosen to head the Institute for Theoretical Physics, a facility that had been created especially for him. In 1892, Planck was promoted to the highest professorial rank, ordinary professor, a post he held until 1926.

Once installed at Berlin, Planck turned his attention to an issue that had long interested his predecessor, the problem of black body radiation. A black body is defined as any object that absorbs all frequencies of radiation when heated and then gives off all frequencies as it cools. For more than a decade, physicists had been trying to find a mathematical law that would describe the way in which a black body radiates heat.

The problem was unusually challenging because black bodies do not give off heat in the way that scientists had predicted that they would. Among the many theories that had been proposed to explain this inconsistency was one by the German physicist Wilhelm Wien and one by the English physicist John Rayleigh. Wien’s explanation worked reasonably well for high frequency black body radiation, and Rayleigh’s appeared to be satisfactory for low frequency radiation. But no one theory was able to describe black body radiation across the whole spectrum of frequencies. Planck began working on the problem of black body radiation in 1896, and by 1900, had found a solution to the problem. That solution depended on a revolutionary assumption, namely that the energy radiated by a black body is carried away in discrete “packages” that were later given the name *quanta* (from the Latin, *quantum*, for “how much”). The concept was revolutionary because physicists had long believed that energy is always transmitted in some continuous form, such as a wave. The wave, like a line in geometry, was thought to be infinitely divisible.

Planck’s suggestion was that the heat energy radiated by a black body be thought of as a stream of “energy bundles,” the magnitude of which is a function of the wavelength of the radiation. His mathematical expression of that concept is relatively simple: $E = h\ 6,50\ ^{-}\ \upsilon$, where E is the energy of the quantum, υ is the wavelength of the radiation, and $h\ 6,50\ ^{-}$ is a constant of proportionality, now known as *Planck’s constant*. Planck found that by making this assumption about the nature of radiated energy, he could accurately describe the experimentally observed relationship between wavelength and energy radiated from a black body. The problem had been solved.

The numerical value of Planck’s constant, $h\ 6,50\ ^{-}$, can be expressed as 6.62×10^{-27} erg second, an expression that is engraved on Planck’s headstone in his final resting place at the Stadtfriedhof Cemetery in Göttingen. Today, Planck’s constant is considered to be a fundamental constant of nature, much like the speed of light and the **gravitational constant**. Although Planck was himself a modest man, he recognized the significance of his discovery. Robert L. Weber in *Pioneers of Science: Nobel Prize Winners in Physics* writes that Planck remarked to his son Erwin during a walk shortly after the discovery of the quantum concept, “Today I have made a discovery which is as important as Newton’s discovery.” That boast

Max Planck. ***Library of Congress.***

has surely been confirmed. The science of physics today can be subdivided into two great eras, classical physics, involving concepts worked out before Planck's discovery of the quantum, and modern physics, ideas that have been developed since 1900, often as a result of that discovery. In recognition of this accomplishment, Planck was awarded the 1918 Nobel Prize in physics.

After completing his study of black body radiation, Planck turned his attention to another new and important field of physics: relativity. Albert Einstein's famous paper on the theory of general relativity, published in 1905, stimulated Planck to look for ways on incorporating his quantum concept into the new concepts proposed by Einstein. He was somewhat successful, especially in extending Einstein's arguments from the field of electromagnetism to that of mechanics. Planck's work in this respect is somewhat ironic in that it had been Einstein who, in another 1905 paper, had made the first productive use of the quantum concept in his solution of the photoelectric problem.

Throughout his life, Planck was interested in general philosophical issues that extended beyond specific research questions. As early as 1891, he had written about the importance of finding large, general themes in physics that could be used to integrate specific phenomena. His book *Philosophy of Physics*, published in 1959, addressed some of these issues. He also looked beyond science itself to ask how his own discipline might relate to philosophy, religion, and society as a whole. Some of his thoughts on the **correlation** of science, art, and religion are presented in his 1935 book, *Die Physik im Kampf um die Weltanschauung*.

Planck remained a devout Christian throughout his life, often attempting to integrate his scientific and religious views. Like Einstein, he was never able to accept some of the fundamental concepts of the modern physics that he had helped to create. For example, he clung to the notion of causality in physical phenomena, rejecting the principles of uncertainty proposed by Heisenberg and others. He maintained his belief in God, although his descriptions of the Deity were not anthropomorphic but more akin to natural law itself.

By the time Planck retired from his position at Berlin in 1926, he had become the second most highly respected scientific figure in **Europe**, if not the world, behind Einstein. Four years after retirement, he was invited to become president of the Kaiser Wilhelm Society in Berlin, an institution that was then renamed the Max Planck Society in his honor. Planck's own prestige allowed him to speak out against the rise of Nazism in Germany in the 1930s, but his enemies eventually managed to have him removed from his position at the Max Planck Society in 1937. During an air raid on Berlin in 1945, Planck's home was destroyed with all of his books and papers. During the last two and a half years of his life, Planck lived with his grandniece in Göttingen, where he died at the age of 89.

See also Quantum electrodynamics (QED)

PLANKTIC FORAMINIFERA • *see* CALCAREOUS OOZE

PLATE TECTONICS

Plate tectonics is the theory explaining geologic changes that result from the movement of **lithospheric plates** over the **asthenosphere** (the molten, ductile, upper portion of the earth's mantle). The visible continents, a part of the lithospheric plates upon which they ride, shift slowly over time as a result of the forces driving plate tectonics. Moreover, plate tectonic theory is so robust in its ability to explain and predict geological processes that it is equivalent in many regards to the fundamental and unifying principles of **evolution** in biology, and nucleosynthesis in **physics** and **chemistry**.

Based upon centuries of cartographic depictions that allowed a good fit between the western coast of **Africa** and the eastern coast of **South America**, in 1858, French geographer Antonio Snider-Pellegrini, published a work asserting that the two continents had once been part of larger single continent ruptured by the creation and intervention of the Atlantic Ocean. In the 1920s, German geophysicist Alfred Wegener's writings advanced the hypothesis of continental drift depicting the movement of continents through an underlying oceanic **crust**. Wegner's hypothesis met with wide skepticism but found support and development in the work and writings of

South African geologist Alexander Du Toit, who discovered a similarity in the **fossils** found on the coasts of Africa and South Americas that derived from a common source.

The technological advances necessitated by the Second World War made possible the accumulation of significant evidence now underlying modern plate tectonic theory.

Plate tectonic theory asserts that Earth is divided into core, mantle, and crust. The crust is subdivided into oceanic and continental crust. The oceanic crust is thin (3–4.3 mi [5–7 km]), basaltic ($<50\%$ SiO_2), dense, and young (<250 million years old). In contrast, the continental crust is thick (18.6–40 mi [30–65 km]), granitic ($<60\%$ SiO_2), light, and old (250–3,700 million years old). The outer crust is further subdivided by the subdivision of the lithospheric plates, of which it is a part, into 13 major plates. These lithospheric plates, composed of crust and the outer layer of the mantle, contain a varying combination of oceanic and continental crust. The lithospheric plates move on top of mantle's asthenosphere.

Boundaries are adjacent areas where plates meet. Divergent boundaries are areas under tension where plates are pushed apart by **magma** upwelling from the mantle. Collision boundaries are sites of compression either resulting in subduction (where lithospheric plates are driven down and destroyed in the molten mantle) or in crustal uplifting that results in **orogeny** (mountain building). At transform boundaries, exemplified by the San Andreas fault, the continents create a shearing force as they move laterally past one another.

New oceanic crust is created at divergent boundaries that are sites of **sea-floor spreading**. Because Earth remains roughly the same size, there must be a concurrent destruction or uplifting of crust so that the net **area** of crust remains the same. Accordingly, as crust is created at divergent boundaries, oceanic crust must be destroyed in areas of subduction underneath the lighter continental crust. The net area is also preserved by continental crust uplift that occurs when less dense continental crusts collide. Because both continental crusts resist subduction, the momentum of collision causes an uplift of crust, forming **mountain chains**. A vivid example of this type of collision is found in the ongoing collision of India with **Asia** that has resulted in the Himalayan Mountains that continue to increase in height each year. This dynamic theory of plate tectonics also explained the formation of **island arcs** formed by rising material at sites where oceanic crust subducts under oceanic crust, the formation of mountain chains where oceanic crust subducts under continental crust (e.g., Andes mountains), and volcanic arcs in the Pacific. The evidence for deep, hot, convective currents combined with plate movement (and concurrent continental drift) also explained the mid-plate "hot spot" formation of volcanic island chains (e.g., Hawaiian Islands) and the formation of rift valleys (e.g., Rift Valley of Africa). **Mid-plate earthquakes**, such as the powerful New Madrid **earthquake** in the United States in 1811, are explained by interplate pressures that bend plates much like a piece of sheet metal pressed from opposite sides.

As with **continental drift theory** two of the proofs of plate tectonics are based upon the geometric fit of the displaced continents and the similarity of **rock** ages and Paleozoic fossils in corresponding bands or zones in adjacent or corresponding geographic areas (e.g., between West Africa and the eastern coast of South America).

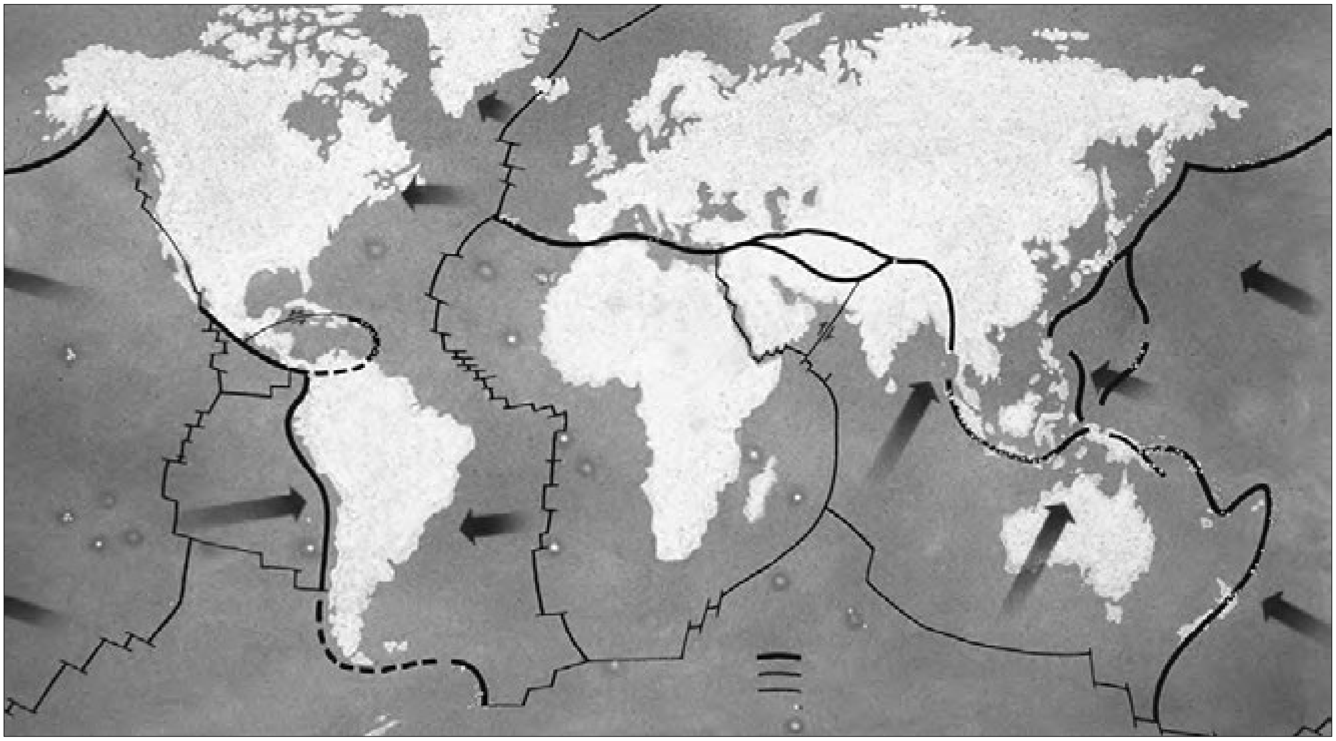
Modern understanding of the structure of Earth is derived in large part from the interpretation of seismic studies that measure the reflection of seismic waves off features in Earth's interior. Different materials transmit and reflect seismic shock waves in different ways, and of particular importance to the theory of plate tectonics is the fact that liquid does not transmit a particular form of seismic wave known as an S-wave. Because the mantle transmits S-waves, it was long thought to be a cooling solid mass. Geologists later discovered that radioactive decay provided a heat source within Earth's interior that made the asthenosphere plasticine (semi-solid). Although solid-like with regard to transmission of seismic S-waves, the asthenosphere contains very low velocity (inches per year) currents of **mafic** (magma-like) molten materials.

Another line of evidence in support of plate tectonics came from the long-known existence of ophiolte suites (slivers of oceanic floor with fossils) found in upper levels of mountain chains. The existence of ophiolte suites are consistent with the uplift of crust in collision zones predicted by plate tectonic theory.

As methods of dating improved, one of the most conclusive lines of evidence in support of plate tectonics derived from the dating of rock samples. Highly supportive of the theory of sea floor spreading (the creation of oceanic crust at a **divergent plate boundary** (e.g., Mid-Atlantic Ridge) was evidence that rock ages are similar in equidistant bands symmetrically centered on the divergent boundary. More importantly, dating studies show that the age of the rocks increases as their distance from the divergent boundary increases. Accordingly, rocks of similar ages are found at similar distances from divergent boundaries, and the rocks near the divergent boundary where crust is being created are younger than the rocks more distant from the boundary. Eventually, radioisotope studies offering improved accuracy and precision in rock dating also showed that rock specimens taken from geographically corresponding areas of South America and Africa showed a very high degree of correspondence, providing strong evidence that at one time these rock formations had once coexisted in an area subsequently separated by movement of lithospheric plates.

Similar to the age of rocks, studies of fossils found in once adjacent geological formations showed a high degree of correspondence. Identical fossils are found in bands and zones equidistant from divergent boundaries. Accordingly, the **fossil record** provides evidence that a particular band of crust shared a similar history as its corresponding band of crust located on the other side of the divergent boundary.

The line of evidence, however, that firmly convinced modern geologists to accept the arguments in support of plate tectonics derived from studies of the magnetic signatures or magnetic orientations of rocks found on either side of divergent boundaries. Just as similar age and fossil bands exist on either side of a divergent boundary, studies of the magnetic orientations of rocks reveal bands of similar magnetic orientation that were equidistant and on both sides of divergent boundaries. Tremendously persuasive evidence of plate tectonics is also derived from **correlation** of studies of the magnetic orientation



Map of the earth with tectonic plate boundaries shown. Convergent zones are shown with thick lines, divergent zones are shown with medium lines, and transform boundaries are shown with thin lines. Arrows indicate the direction of plate motion. Large orange dots represent "hot spots" and small orange dots represent volcanoes. ***David Hardy/Science Photo Library. Reproduced by permission.***

of the rocks to known changes in Earth's **magnetic field** as predicted by electromagnetic theory. Paleomagnetic studies and discovery of polar wandering, a magnetic orientation of rocks to the historical location and polarity of the magnetic poles as opposed to the present location and polarity, provided a coherent map of continental movement that fit well with the present distribution of the continents.

Paleomagnetic studies are based upon the fact that some hot **igneous rocks** (formed from volcanic magma) contain varying amounts of **ferromagnetic minerals** (e.g., Fe_3O_4) that magnetically orient to the prevailing magnetic field of Earth at the time they cool. Geophysical and electromagnetic theory provides clear and convincing evidence of multiple polar reversals or polar flips throughout the course of Earth's history. Where rock formations are uniform—i.e., not grossly disrupted by other geological processes—the magnetic orientation of magnetite-bearing rocks can also be used to determine the approximate **latitude** the rocks were at when they cooled and took on their particular magnetic orientation. Rocks with a different orientation to the current orientation of Earth's magnetic field also produce disturbances or unexpected readings (anomalies) when scientists attempt to measure the magnetic field over a particular area.

This overwhelming support for plate tectonics came in the 1960s in the wake of the demonstration of the existence of symmetrical, equidistant magnetic anomalies centered on the Mid-Atlantic Ridge. Geologists were comfortable in accepting these magnetic anomalies located on the sea floor as evidence of sea floor spreading because they were able to correlate these anomalies with equidistant radially distributed magnetic anomalies associated with outflows of **lava** from land-based volcanoes.

Additional evidence continued to support a growing acceptance of tectonic theory. In addition to increased energy demands requiring enhanced exploration, during the 1950s there was an extensive effort, partly for military reasons related to what was to become an increasing reliance on submarines as a nuclear deterrent force, to map the ocean floor. These studies revealed the prominent undersea ridges with undersea rift valleys that ultimately were understood to be divergent plate boundaries. An ever-growing network of seismic reporting stations, also spurred by the Cold War need to monitor atomic testing, provided substantial data that these areas of divergence were tectonically active sites highly prone to earthquakes. Maps of the global distribution of earthquakes readily identified stressed plate boundaries. Improved mapping also made it possible to view the retrofit of continents in terms of the fit between the true extent of the continental crust instead of the current coastlines that are much variable to influences of **weather** and ocean levels.

In his important 1960 publication, *History of Ocean Basins*, geologist and U.S. Navy Admiral Harry Hess (1906–1969) provided the missing explanatory mechanism for plate tectonic theory by suggesting that the thermal convection currents in the asthenosphere provided the driving force behind plate movements. Subsequent to Hess's book, geologists

Drummond Matthews (1931–1997) and Fred Vine (1939–1988) at Cambridge University used magnetometer readings previously collected to correlate the paired bands of varying **magnetism** and anomalies located on either side of divergent boundaries. Vine and Matthews realized that magnetic data revealing strips of polar reversals symmetrically displaced about a divergent boundary confirmed Hess's assertions regarding seafloor spreading.

See also Dating methods; Earth, interior structure; Fossil record; Fossils and fossilization; Geologic time; Hawaiian Island formation; Lithospheric plates; Mantle plumes; Mapping techniques; Mid-ocean ridges and rifts; Mohorovicic discontinuity (Moho); Ocean trenches; Rifting and rift valleys; Subduction zone

PLATEAU • *see* LANDFORMS

PLEISTOCENE EPOCH

In **geologic time**, the Pleistocene Epoch represents the first epoch in current **Quaternary Period** (also termed the Anthropogene Period) of the **Cenozoic Era** of the **Phanerozoic Eon**. The Pleistocene Epoch spans the time between roughly 2.6 million years ago (mya) and onset of the current **Holocene Epoch** 10,000 to 11,000 years ago.

The Quaternary Period contains two geologic epochs. The earliest epoch, the Pleistocene Epoch is further subdivided into (from earliest to most recent) Gelasian and Calabrian stages. The Calabrian stage is also frequently replaced by a series of geologic stages, from earliest to most recent, including the Danau, Donau-Günz, Günzian, Günz-Mindel, Mindelian, Mindel-Riss, Rissian, Riss-Würm, and Würmian stages.

During the Pleistocene Epoch, Earth's continents almost completely assumed their modern configuration.

Glaciation cycles dominated the major climatic changes of the Pleistocene Epoch. There were at least four distinct glacial advances and recessions. In addition to tremendous **landscape evolution**, climatic cooling contributed to mass extinction in selective areas of the world, but not nearly on the scale as earlier mass extinctions.

The size of land mammals generally increased throughout the Pleistocene Epoch and the **fossil record** established that during the Pleistocene Epoch, hominid (human-like) species became established and evolved into humans (*Homo sapiens*).

Near the start of the Pleistocene Epoch, a number of related species (e.g., *Australopithecus afarensis*) lived and became extinct before modern humankind (*Homo sapiens*) appeared. Early in the Pleistocene Epoch, *Homo habilis* and *Homo rudolfensis* lived and became extinct. Their extinctions are dated to approximately the appearance of *Homo ergaster*, a species some anthropologists argue is one of the earliest identifiable direct ancestors of *Homo erectus*. Although often confused with *Homo erectus*, many scientists assert that *Homo ergaster* is a common ancestor that lead more directly to the subsequent development of *Homo heidelbergensis*, *Homo neanderthalensis*, and humans (*Homo sapiens*).

The last major **impact crater** with a diameter over 31 mi (50 km) struck Earth near what is now Kara-Kul, Tajikistan, at the start of the Pleistocene Epoch. The last major impacts producing craters greater than 6.2 mi (10 km) in diameter occurred during the Pleistocene Epoch about 1.2 million years ago in what are now Kazakhastan and Ghana.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossils and fossilization; Glacial landforms; Glaciers; Historical geology; Ice ages; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Precambrian; Proterozoic Era; Silurian Period; Triassic Period

PLIOCENE EPOCH

In **geologic time**, the Pliocene Epoch occurs during the **Tertiary Period** (65 million years ago [mya] to 2.6 mya) of the **Cenozoic Era** of the **Phanerozoic Eon**. The Tertiary Period is sometimes divided into—or referred to in terms of—a Paleogene Period (65 mya to 23 mya) and a Neogene Period (23 mya to 2.6 mya). The Pliocene Epoch is the last epoch on the Tertiary Period or, in the alternative, the last epoch in the Neogene Period.

The Pliocene Epoch spans the time 5 mya to 2.6 mya.

The Pliocene Epoch is further subdivided into Zanclian (5 mya to 3.9 mya) and Placenzian (3.9 mya to 2.6 mya) stages.

By the end Pliocene Epoch, Earth's continents assumed their modern configuration. The Pacific Ocean separated **Asia** and **Australia** from **North America** and **South America**; the Atlantic Ocean separated North and South America from **Europe** (Eurasian plate) and **Africa**. The Indian Ocean filled the basin between Africa, India, Asia, and Australia. The Indian plate driving against and under the Eurasian plate uplifted both and resulted in rapid mountain building. As a result of the ongoing collision, ancient oceanic **crust** bearing marine **fossils** was uplifted into the Himalayan chain. The collision between the Indian and Eurasian plate continues. The reemergence of the land bridge between North America and South America at the isthmus of Panama about 3 mya allowed migration of species and mixing of gene pools in subspecies.

Climatic cooling increased during Pliocene Epoch, and grasslands continued the rapid development found in the **Miocene Epoch**. Eventually, **glaciation** became well established and a general glacier advance started that continued into the subsequent **Pleistocene Epoch** of the **Quaternary Period**.

The Pliocene Epoch spanned that period of geologic time during which the **evolution** of humans becomes increasingly well documented in the **fossil record**. Notable in the development of primates and human evolution, are fossilized remains of *Ardipithecus ramidus*, *Australopithecus anamensis*, *Australopithecus afarensis*, *Australopithecus garhi*, and *Australopithecus africanus* that date to the Pliocene Epoch.

Although these species became extinct during the Pliocene Epoch, they at a minimum co-existed with the ancestors of humans (*Homo sapiens*); analysis of remains indicate that these species walked upright. Anthropologists argue that apes and humans diverged six to eight mya from a common ancestor that lived during the Miocene Epoch. By the end of the Pliocene Epoch, the subsequent extinctions of *Homo habilis* and *Homo rudolfensis* were almost contemporaneous with the appearance of *Homo ergaster*, a species some anthropologists argue is one of the earliest identifiable direct ancestors of *Homo sapiens*.

The last major **impact crater** with a diameter over 31 mi (50 km) struck Earth near what is now Kara-Kul, Tajikistan at the Pliocene Epoch and Pleistocene Epoch geologic time boundary.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Evolutionary mechanisms; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Precambrian; Proterozoic Era; Silurian Period; Triassic Period

PLUTO • *see* SOLAR SYSTEM

PLUTON AND PLUTONIC BODIES

Plutons or plutonic bodies are masses of intrusive igneous **rock** that have solidified underground, as opposed to volcanic (extrusive) rocks that solidify only after erupting onto the surface. Plutonic rocks are characterized by a coarse crystalline texture in which individual **crystals** can be easily seen by the naked eye. The word plutonic is derived from the name of Pluto, the Greek god of the underworld.

The composition of plutonic rocks ranges from **mafic** (gabbro and diorite) to **felsic** (granodiorite and **granite**), and the coarse crystalline texture develops because plutonic rocks are insulated by the surrounding **country rock** and cool very slowly. Plutons, however, are classified according to their size, shape, and relationship to the surrounding rock rather than the kind of rock composing the pluton. Of the many varieties of plutons, four types are described below.

Batholiths are large plutons with more than about 38.6 mi^2 (100 km^2) of surface exposure in map view, such as the Sierra Nevada **batholith** that forms the core of the Sierra Nevada mountain range. Batholiths are discordant plutons, meaning that they cut across the layering of the rocks that they have intruded, and generally do not have an identifiable bottom. Detailed studies have shown that batholiths are most commonly composed of many different igneous intrusions with chemical compositions that vary in **space** and time.

Laccoliths are concordant plutons that follow the existing rock layers and push up overlying strata to form an intrusion that is mushroom-shaped in cross section, as exemplified by the Henry Mountains in Utah. Laccoliths tend to be circular, or nearly so, in map view and less than approximately 5 mi (8 km) in diameter. The thickness of laccoliths can range from a few meters near the edges to several hundred meters near the center of the intrusion. Laccoliths are understood to form when **magma** rises through a feeder **dike**, then begins to spread laterally along a plane of weakness such as a **bedding** plane separating different layers of sedimentary rock.

Two relatively common kinds of small plutons, both tabular in shape, are dikes and sills. Dikes are discordant whereas sills are concordant. In both cases, the thickness of the pluton is very small compared to its lateral extent.

See also Dike; Granite; Igneous rocks; Intrusive cooling; Sill

POINTBARS • *see* CHANNEL PATTERNS

POLAR AXIS AND TILT

The polar axis is an imaginary line that extends through the north and south geographic poles. Earth rotates on its axis as it revolves around the **Sun**. Earth's axis is tilted approximately 23.5 degrees to the plane of the ecliptic (the plane of planetary orbits about the Sun or the apparent path of the Sun across in imaginary celestial sphere). The tilt of the polar axis is principally responsible for variations in solar illumination (**insolation**) that result in the cyclic progressions of the **seasons**.

Earth rotates about the polar axis at approximately 15 angular degrees per hour and makes a complete **rotation** in 23.9 hours. The length of day has changed throughout Earth's history and as rotation slows, the time to complete one rotation about the polar axis will continue to increase. Rate of rotation is a function of planet's mass and orbital position. As Earth rotates on its polar axis, it makes a slightly elliptical orbital revolution about the Sun in 365.26 days. The rates of rotation and revolution are functions of a planet's mass and orbital position.

Rotation about the polar axis results in a diurnal cycle of night and day, and causes the apparent motion of the Sun across the imaginary celestial sphere. The celestial sphere is an imaginary **projection** of the Sun, stars, planets, and all astronomical bodies upon an imaginary sphere surrounding Earth. The celestial sphere is a useful conceptual and tracking remnant of the geocentric theory of the ancient Greek astronomer **Ptolemy**.

During revolution about the Sun, Earth's polar axis exhibits parallelism to Polaris (also known as the North Star). Although observing parallelism, the orientation of Earth's polar axis exhibits precession—a circular wobbling exhibited by gyroscopes—that results in a 28,000-year-long precessional cycle. Currently, Earth's polar axis points roughly in the direction of Polaris (the North Star). As a result of precession, over the next 11,00 years, Earth's axis will precess or wobble so that it assumes an orientation toward the star Vega.

Precession also affects the dates of solstice. At the summer solstice (currently occurring about June 21), the north polar axis points in a direction 23.5 degrees from vertical—

relative to the plane of the ecliptic—toward the Sun. At the winter solstice (currently occurring about December 21) the north polar axis points away from the Sun. At equinox neither pole is tilted toward the Sun but rather in a 23.5 degree tilt from vertical oriented at right angles to line between an imaginary line drawn between the Sun and Earth.

Annual changes in the orientation of the polar axis relative to the Sun result in the apparent movement of the path of the Sun (the ecliptic) across the celestial sphere. The maximum variation in the altitude of the ecliptic above the horizon is two times the polar axial tilt (i.e., 47 degrees).

Milankovitch cycles attempt to integrate and relate changes in Earth's orbital eccentricity, polar axial tilt, and polar axis precession to changes in **climate** (e.g., **glaciation** cycles).

The International **Latitude** Service was established in 1899 to collect data concerning polar axial motion. In 1962, the International Polar Motion Service assumed data collection. In 1988, the International Polar Motion Service, the Earth Rotation Division of the Bureau International de l'Heure, combined operations to form the International Earth Rotation Service. A number of geodetic measuring techniques—including VLBI (Very Long Baseline Interferometry), lunar laser ranging, and the current Global Positioning System (**GPS**) contribute to accurate measurements concerning polar wobbling and rotational rates.

See also Astrolabe; Astronomy; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Revolution and rotation; Solar illumination: Seasonal and diurnal patterns

POLAR ICE

The polar **ice** caps cover the North and South Poles and their surrounding territory, including the entire continent of **Antarctica** in the south, the Arctic Ocean, the northern part of Greenland, parts of northern Canada, and bits of Siberia and Scandinavia also in the north. Polar ice caps are dome-shaped sheets of ice that feed ice to other glacial formations, such as ice sheets, ice fields, and ice islands. They remain frozen year-round, and they serve as sources for **glaciers** that feed ice into the polar **seas** in the form of **icebergs**. Because the polar ice caps are very cold (temperatures in Antarctica have been measured to –126.8°F [–88°C]) and exist for a long time, the caps serve as deep-freezes for geologic information that can be studied by scientists. Ice cores drawn from these regions contain important data for both geologists and historians about paleoclimatology and give clues about the effects human activities are currently having on the world.

Polar ice caps also serve as reservoirs for huge amounts of the earth's **water**. Geologists suggest that three-quarters of the world's fresh water is frozen at the North and South Pole. Most of this **freshwater** ice is in the Southern Hemisphere. The Antarctic ice cap alone contains over 90% of the world's glacial ice, sometimes in huge sheets over 2.5 mi (4 km) deep and averaging 1.5 mi (2 km) deep across the continent. It has been estimated that enough water is locked up in Antarctica to raise sea levels around the globe over 200 ft (61 m), drowning most of the world's major cities, destroying much of the world's food-producing capacity, and ending civilization.

Although the polar ice caps have been in existence for millions of years, scientists disagree over exactly how long they have survived in their present form. It is generally agreed that the polar cap north of the Arctic Circle, which covers the Arctic Ocean, has undergone contraction and expansion through some 26 different glaciations in just the past few million years. Parts of the Arctic have been covered by the polar ice cap for at least the last five million years, with estimates ranging up to 15 million. The Antarctic ice cap is more controversial; although many scientists believe extensive ice has existed there for 15 million years, others suggest that volcanic activity on the western half of the continent it covers causes the ice to decay, and the current south polar ice cap is therefore no more than about three million years old.

At least five times since the formation of the earth, because of changes in global **climate**, the polar ice has expanded north and south toward the equator and has stayed there for at least a million years. The earliest of these known **ice ages** was some two billion years ago, during the Huronian Epoch of the **Precambrian** Era. The most recent ice age began about 1.7 million years ago in the **Pleistocene Epoch**. It was characterized by a number of fluctuations in North polar ice, some of which expanded over much of modern **North America** and **Europe**, covered up to half of the existing continents, and measured as much as 1.8 mi (3 km) deep in some places. These glacial expansions locked up even more water, dropping sea levels worldwide by more than 30 ft (100 m). Animal species that had adapted to cold **weather**, like the mammoth, thrived in the polar conditions of the Pleistocene glaciations, and their ranges stretched south into what is now the southern United States.

The glaciers completed their retreat and settled in their present positions about 10,000–12,000 years ago. There have been other fluctuations in global temperatures on a smaller scale, however, that have sometimes been known popularly as ice ages. The 400-year period between the fourteenth and the eighteenth centuries is sometimes called the Little Ice Age. Contemporaries noted that the Baltic Sea froze over twice in the first decade of the 1300s. Temperatures in Europe fell enough to shorten the growing season, and the production of grain in Scandinavia dropped precipitously as a result. The Norse communities in Greenland could no longer be maintained and were abandoned by the end of the fifteenth century. Scientists believe that we are currently in an interglacial period, and that North polar ice will again move south some time in the next 23,000 years.

Scientists believe the growth of polar ice caps can be triggered by a combination of several global climactic factors. The major element is a small drop (perhaps no more than 15°F [9°C]) in average world temperatures. The factors that cause this drop can be very complex. They include fluctuations in atmospheric and oceanic **carbon dioxide** levels, increased amounts of dust in the atmosphere, heightened winds—especially in equatorial areas—and changes in surface oceanic currents. The Milankovitch theory of glacial cycles also cites as factors small variations in Earth's orbital path around the **Sun**, which in the long term could influence the expansion and contraction of the polar ice caps. Computer models based on the Milankovitch theory correlate fairly closely with observed behavior of **glaciation** over the past 600 million years.

Scientists use material preserved in the polar ice caps to chart these changes in global glaciation. By measuring the relationship of different **oxygen** isotopes preserved in ice cores, they have determined both the mean **temperature** and the amount of dust in the atmosphere in these latitudes during the recent ice ages. Single events, such as **volcanic eruptions** and variations in solar activity and sea level, are also recorded in polar ice. These records are valuable not only for the information they provide about past glacial periods; they serve as a standard to compare against the records of more modern periods.

The process of **global warming**, which has been documented by scientific investigation, is also reflected in the ice caps. Should global warming continue unchecked, scientists warn, it could have a drastic effect on polar ice. Small variations over a short period of time could shrink the caps and raise world sea levels. Even a small rise in sea level could affect a large percentage of the world's population, and it could effectively destroy major cities like New York. Ironically, global warming could also delay or offset the effects of the coming ice age.

See also Glacial landforms

POLYMORPH

A polymorph is a chemical composition that can crystallize into more than one type of structure. This results in different **minerals** with identical compositions and distinguished by their crystallography.

Some common examples of polymorphs are calcite and aragonite. The composition of these two minerals is $CaCO_3$, but calcite is rhombohedral while aragonite is orthorhombic. **Diamond** and **graphite**, both of which are pure **carbon**, are also polymorphs. Diamond, however, is cubic while graphite is hexagonal. Pyrite is the cubic form of FeS_2, marcasite, the orthorhombic version.

A single chemical composition that can form polymorphs does so as a response to varying conditions of formation. The **temperature**, pressure, and chemical environment all affect the crystallization process and can determine the resulting polymorph. For example, diamond requires very high pressure to crystallize, while graphite forms at lower pressures. For the composition $CaCO_3$, calcite is the high temperature-low pressure polymorph while aragonite forms at higher pressures and lower temperatures.

Many polymorphs are only stable within a certain range of conditions and solid-state transitions from one polymorph to another are possible. When low-quartz, which is rhombohedral, is heated to above 1063°F (573°C), it instantaneously goes through an internal structural displacement, or shift, to form hexagonal high-quartz. This type of polymorphic transition is reversible if the temperature is lowered. Other polymorphic transitions involve extensive internal rearrangement and reconstruction of the crystal and subsequently require significantly more energy. The examples of diamond-graphite, pyrite-marcasite, and calcite-aragonite are all known as reconstructive transitions. The large amounts of energy required to effect these polymorphic changes makes the resulting mineral more stable and the process less reversible than with a displacive transition.

See also Crystals and crystallography; Mineralogy

PONNAMPERUMA, CYRIL (1923-1994)

Sri Lankan-born American chemist

Cyril Ponnamperuma, an eminent researcher in the field of chemical evolution, rose through several National Aeronautics and Space Administration (NASA) divisions as a research chemist to head the Laboratory of Chemical Evolution at the University of Maryland, College Park. His career focused on explorations into the **origin of life** and the "primordial soup" that contained the precursors of life. In this search, Ponnamperuma took advantage of discoveries in such diverse fields as molecular biology and astrophysics.

Born in Galle, Ceylon (now Sri Lanka) on October 16, 1923, Cyril Andres Ponnamperuma was educated at the University of Madras (where he received a B.A. in Philosophy, 1948), the University of London (B.Sc., 1959), and the University of California at Berkeley (Ph.D., 1962). His interest in the origin of life began to take clear shape at the Birkbeck College of the University of London, where he studied with J. D. Bernal, a well-known crystallographer. In addition to his studies, Ponnamperuma also worked in London as a research chemist and radiochemist. He became a research associate at the Lawrence Radiation Laboratory at Berkeley, where he studied with Melvin Calvin, a Nobel laureate and experimenter in chemical evolution.

After receiving his Ph.D. in 1962, Ponnamperuma was awarded a fellowship from the National Academy of Sciences, and he spent one year in residence at NASA's Ames Research Center in Moffet Field, California. After the end of his associate year, he was hired as a research scientist at the center and became head of the chemical evolution branch in 1965.

During these years, Ponnamperuma began to develop his ideas about chemical evolution, which he explained in an article published in *Nature.* Chemical evolution, he explained, is a logical outgrowth of centuries of studies both in **chemistry** and biology, culminating in the groundbreaking 1953 discovery of the structure of deoxyribonucleic acid (DNA) by James Watson and Francis Crick. Evolutionist Charles Darwin's studies affirming the idea of the "unity of all life" for biology could be extended, logically, to a similar notion for chemistry: protein and nucleic acid, the essential elements of biological life, were, after all, chemical.

In the same year that Watson and Crick discovered DNA, two researchers from the University of Chicago, Stanley Lloyd Miller and **Harold Urey**, experimented with a primordial soup concocted of the elements thought to have made up Earth's early atmosphere—methane, ammonia, hydrogen, and **water**. They sent electrical sparks through the mixture, simulating a **lightning** storm, and discovered trace amounts of amino acids.

During the early 1960s, Ponnamperuma began to delve into this primordial soup and set up variations of Miller and Urey's original experiment. Having changed the proportions of the elements from the original Miller-Urey specifications slightly, Ponnamperuma and his team sent first high-energy electrons, then ultraviolet light through the mixture, attempting to recreate the original conditions of the earth before life. They succeeded in creating large amounts of adenosine triphosphate (ATP), an amino acid that **fuels** cells. In later experiments with the same concoction of primordial soup, the team was able to create the nucleotides that make up nucleic acid—the building blocks of DNA and ribonucleic acid (RNA).

In addition to his work in prebiotic chemistry, Ponnamperuma became active in another growing field: exobiology, or the study of extraterrestrial life. Supported in this effort by NASA, he was able to conduct research on the possibility of the evolution of life on other planets. Theorizing that life evolved from the interactions of chemicals present elsewhere in the universe, he saw the research possibilities of spaceflight. He experimented with lunar **soil** taken by the *Apollo 12* space mission in 1969. As a NASA investigator, he also studied information sent back from Mars by the unmanned Viking, Pioneer, and Voyager probes in the 1970s. These studies suggested to Ponnamperuma that Earth is the only place in the **solar system** where there is life.

In 1969, a meteorite fell to Earth in Muchison, **Australia**. It was retrieved still warm, providing scientists with fresh, uncontaminated material from space for study. Ponnamperuma and other scientists examined pieces of the meteorite for its chemical make-up, discovering numerous amino acids. Most important, among those discovered were the five chemical bases that make up the nucleic acid found in living organisms. Further interesting findings provided tantalizing but puzzling clues about chemical evolution, including the observation that light reflects both to the left and to the right when beamed through a solution of the meteorite's amino acids, whereas light reflects only to the left when beamed through the amino acids of living matter on Earth.

Ponnamperuma's association with NASA continued as he entered academia. In 1979, he became a professor of chemistry at the University of Maryland and director of the Laboratory of Chemical Evolution—established and supported in part by the National Science Foundation and by NASA. He continued active research and experimentation on meteorite material. In 1983, an article in the science section of the *New York Times* explained Ponnamperuma's chemical evolution theory and his findings from the Muchison meteorite experiments. He reported the creation of all five chemical bases of living matter in a single experiment that consisted of bombarding a primordial soup mixture with **electricity**.

Ponnamperuma's contributions to scholarship include hundreds of articles. He wrote or edited numerous books, some in collaboration with other chemists or exobiologists, including annual collections of papers delivered at the College Park Colloquium on Chemical Evolution. He edited two journals, *Molecular Evolution* (from 1970 to 1972) and *Origins of Life* (from 1973 to 1983). In addition to traditional texts in the field of chemical evolution, he also co-authored a software program entitled "Origin of Life," a simulation model intended to introduce biology students to basic concepts of chemical evolution.

Although Ponnamperuma became an American citizen in 1967, he maintained close ties to his native Sri Lanka, even becoming an official governmental science advisor. His professional life has included several international appointments. He was a visiting professor of the Indian Atomic Energy Commission (1967); a member of the science faculty at the Sorbonne (1969); and director of the UNESCO Institute for Early Evolution in Ceylon (1970). His international work included the directorship of the Arthur C. Clarke center, founded by the science fiction writer, a Sri Lankan resident.

Ponnamperuma was a member of the Indian National Science Academy, the American Association for the Advancement of Science, the American Chemical Society, the Royal Society of Chemists, and the International Society for the Study of the Origin of Life, which awarded him the A. I. Oparin Gold Medal in 1980. In 1991, Ponnamperuma received a high French honor—he was made a Chevalier des Arts et des Lettres. Two years later, the Russian Academy of Creative Arts awarded him the first Harold Urey Prize. In October 1994, he was appointed to the Pontifical Academy of Sciences in Rome. He married Valli Pal in 1955; they had one child. Ponnamperuma died on December 20, 1994.

See also Evolutionary mechanisms; Miller-Urey experiment

POROSITY AND PERMEABILITY

Porosity and permeability are two of the primary factors that control the movement and storage of fluids in rocks and sediments. They are intrinsic characteristics of these geologic materials. The exploitation of natural resources, such as **groundwater** and **petroleum**, is partly dependent on the properties of porosity and permeability.

Porosity is the ratio of the volume of openings (voids) to the total volume of material. Porosity represents the storage capacity of the geologic material. The primary porosity of a sediment or **rock** consists of the spaces between the grains that make up that material. The more tightly packed the grains are, the lower the porosity. Using a box of marbles as an example, the internal dimensions of the box would represent the volume of the sample. The **space** surrounding each of the spherical marbles represents the void space. The porosity of the box of marbles would be determined by dividing the total void space by the total volume of the sample and expressed as a percentage.

The primary porosity of unconsolidated sediments is determined by the shape of the grains and the range of grain sizes present. In poorly sorted sediments, those with a larger range of grain sizes, the finer grains tend to fill the spaces between the larger grains, resulting in lower porosity. Primary porosity can range from less than one percent in crystalline rocks like **granite** to over 55% in some soils. The porosity of some rock is increased through fractures or solution of the material itself. This is known as secondary porosity.

Permeability is a measure of the ease with which fluids will flow though a porous rock, sediment, or **soil**. Just as with porosity, the packing, shape, and sorting of granular materials control their permeability. Although a rock may be highly porous, if the voids are not interconnected, then fluids within the closed, isolated pores cannot move. The degree to which pores within the material are interconnected is known as effective porosity. Rocks such as **pumice** and shale can have high porosity, yet can be nearly impermeable due to the poorly interconnected voids. In contrast, well-sorted **sandstone** closely replicates the example of a box of marbles cited above. The rounded **sand** grains provide ample, unrestricted void spaces that are free from smaller grains and are very well linked. Consequently, sandstones of this type have both high porosity and high permeability.

The range of values for permeability in geologic materials is extremely large. The most conductive materials have permeability values that are millions of times greater than the least permeable. Permeability is often directional in nature. The characteristics of the interstices of certain materials may cause the permeability to be significantly greater in one direction. Secondary porosity features, like fractures, frequently have significant impact on the permeability of the material. In addition to the characteristics of the host material, the viscosity and pressure of the fluid also affect the rate at which the fluid will flow.

See also Aquifer; Hydrogeology

POTENTIAL ENERGY • *see* ENERGY TRANSFORMATIONS

PRAIRIE

The term prairie is an ecological term used to describe a geologic plain covered by mostly grass. Prairies have been subdivided into smaller, more specific categories by the type of vegetation they support. Short grass and long grass prairies historically covered most of the central portion of the United States. However, the grasses have been replaced by urbanization and agriculture, but the plain still exists.

The Great Plains of the United States support one of the most famous prairies in the world. As with all prairies, the **area** is supported underneath by a firm **bedrock**. In this case, the bedrock is composed of **limestone** deposited by a relatively continuous series of ancient **seas** that advanced and retreated across America and Canada for millions of years. **Dolomite**, containing high levels of magnesium, is the primary building block of the **bedforms**.

Overlying the bedrock are massive and extensive fossil **coral reefs**. These ancient reefs are quite impressive. They began to form in the warm shallow seas after the Silurian about 400 million years ago. Growth was intermittent as the seas transgressed (grew) and regressed (receded) in a cyclic pattern.

During the last 1.9 million years, the entire upper North American continent was covered with **ice**. The ice sheets grew and shrank according to global climate fluctuations. The grinding of the massive ice sheets produced a fine sediment called glacial **till**. The meltwaters of the **glaciers** moved the till away from the sheets and out onto the dolomitic plain in a process known as glacial drift. The drift formed many distinctive structures including eskers, **moraines**, and kettles. The sequences of advancing ice are recorded in the layers of the sediments. What was once considered a distinct pattern of a few ice advances is now understood to be a complicated chronology of at least 29 different episodes. The last identifiable age of ice deposition is called the Wisconsin **glaciation**. This event stripped much of the prairie of high physiographic features while depositing the characteristic soils of the current prairie.

The soils that are high in carbonates are not very rich for growing vegetation. Trees are exposed to extremes of temperatures and varying **precipitation**. They do not fare as well as the hardier grasses. Consequently, the **evolution** of grasses has been intimately tied with the development of the prairie. The prairies have been threatened by the introduction of foreign grass types. Some areas of the prairie have been set aside as national grasslands and non-native grasses are sought out and removed. The majesty of the prairie still exists in these historic places.

See also Glacial landforms; Ice ages; Marine transgression and marine regression; Soil and soil horizons

PRECAMBRIAN

In **geologic time**, Precambrian time encompasses the time from Earth's formation, approximately 4.5 billion years ago, until the start of the Cambrian approximately 540 million years ago (mya). Because the Precambrian is not a true geologic eon, era, period, or epoch, geologists often refer to it as Precambrian time (or simply, Precambrian). Precambrian time represents the vast bulk of Earth's geologic history and covers nearly 90% of Earth's history.

Although scientists do not yet know all the exact steps by which the earth formed, cooled, and took on its approximate shape and physical characteristics, a good deal of reliable evidence can be inferred from studies that concentrate on the formation of landmass, **oceans**, and atmosphere. Astrophysical data—and theories of **physics** that explain the **evolution** of physical law and nucelosynthesis—make these studies of Earth's formation both possible and reliable because the same laws of physics and **chemistry** that exist now operated during the formation of Earth's **solar system**.

Radiological dating provides overwhelming evidence that dates known terrestrial (Earth origin) **rock** specimens to more than 3.6 billion years old. Earth and lunar meteorites date to 4.5 billion years.

Precambrian time is subdivided into Hadean time (4.5 billion years ago to 3.8 billion years ago); **Archean** time (3.8 billion years ago to 2.5 billion years ago; Paleoproterozoic time

(2.5 billion years ago to 1.6 billion years ago); Mesoproterozoic time (1.6 billion years ago to 900 million years ago); and Neoproterozoic time (900 million years ago to 540 mya).

Hadean time represents the time during which the solar system formed. During the subsequent course of Precambrian time, Earth's **lithospheric plates** formed and the mechanisms of geologic change described by modern plate tectonic theory began to occur. During Precambrian time, life arose on Earth. The oldest known fossil evidence (fig tree group fossils in what is now **Africa**) dates to early in Archaean time. During the Paleoproterozoic, Earth's primitive atmosphere made a transition to an **oxygen** rich atmosphere. Soon thereafter in geologic time, i.e. within a few hundred million years, there is evidence of the earliest appearance of eukaryotes (organisms with a true nucleus containing DNA). Evidence of the oldest fossilized animal remains dates to the end of Neoproterozic time.

The extensive debris field that existed in the early solar system assured frequent bombardment of Earth's primitive atmosphere by **asteroids** and **comets**. Despite the consuming effects of geological **weathering** and **erosion**, evidence of Precambrian time impacts dating almost 2.0 billion years ago have been found in what are now South Africa and Canada.

See also Cambrian Period; Cenozoic Era; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miller-Urey experiment; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Tertiary Period; Triassic Period

PRECIOUS METALS

Gold, silver, and platinum have historically been valued for their beauty and rarity. They are the precious **metals**. Platinum usually costs slightly more than gold, and both metals are about 80 times more costly than silver. Precious metal weights are given in Troy ounces (named for Troyes, France, known for its fairs during the Middle Ages) a unit approximately 10% larger than 1 oz (28.35 g).

The ancients considered gold and silver to be of noble birth compared to the more abundant metals. Chemists have retained the term noble to indicate the resistance these metals have to **corrosion**, and their natural reluctance to combine with other elements.

The legends of King Midas and Jason's search for the golden fleece hint at prehistoric mankind's early fascination with precious metals. The proof comes in the gold and silver treasure found in ancient Egyptian tombs and even older Mesopotamian burial sites.

The course of recorded history also shows twists and turns influenced to a large degree by precious metals. It was Greek silver that gave Athens its Golden Age, Spanish gold and silver that powered the Roman Empire's expansion, and the desire for gold that motivated Columbus to sail west across the Atlantic. The exploration of Latin America was driven in large part by the search for gold, and the Jamestown settlers in **North America** had barely gotten their "land legs" before they began searching for gold. Small amounts of gold found in North Carolina, Georgia, and Alabama played a role in the 1838 decision to remove the Cherokee Indians to Oklahoma. The California gold rush of 1849 made California a state in 1850, and California gold fueled northern industry and backed up union currency, two major factors in the outcome of the Civil War.

Since ancient times, gold has been associated with the **Sun**. Its name is believed to be derived from a Sanskrit word meaning "to shine," and its chemical symbol (Au) comes from *aurum*, Latin for "glowing dawn." Pure gold has an attractive, deep yellow color and a specific **gravity** of 19.3. Gold is soft enough to scratch with a fingernail, and the most malleable of metals. A block of gold about the size of a sugar cube can be beaten into a translucent film some 27 ft (8 m) on a side. Gold's purity is expressed either as fineness (parts per 1,000) or in karats (parts per 24). An **alloy** containing 50% gold is 500 fine or 12 karat gold. Gold resists corrosion by air and most chemicals but can be dissolved in a mixture of nitric and hydrochloric acids, a solution called *aqua regia* because it dissolves the "king of metals".

Gold is so rare that one ton of average **rock** contains only about eight pennies worth of gold. Gold ore occurs where geologic processes have concentrated gold to at least 250 times the value found in average rock. At that concentration, there is still one million times more rock than gold and the gold is rarely seen. Ore with visible gold is fabulously rich.

Gold most commonly occurs as a pure metal called native gold or as a natural alloy with silver called electrum. Gold and silver combined with tellurium are of local importance. Gold and silver tellurides are found, for example, in the mountains around the old mining boom-town of Telluride, Colorado. Gold is found in a wide variety of geologic settings, but placer gold and gold veins are the most economically important.

Placer gold is derived from gold-bearing rock from which the metal has been freed by **weathering**. Gravity and running **water** then combine to separate the dense grains of gold from the much lighter rock fragments. Rich concentrations of gold can develop above deeply weathered gold veins as the lighter rock is washed away. The "Welcome Stranger" from the gold fields of Victoria, **Australia**, is a spectacular 158–16 (71.5-kg) example of this type of occurrence.

Gold washed into mountain streams also forms placer deposits where the stream's velocity diminishes enough to deposit gold. Stream placers form behind boulders and other obstructions in the streambed, and where a tributary stream merges with a more slowly moving river. Placer gold is also found in gravel bars where it is deposited along with much larger rocky fragments.

The discovery of placer gold set off the California gold rush of 1849 and the rush to the Klondike in 1897. The largest river placers known are in Siberia, Russia. Gold-rich sands there are removed with jets of water, a process known as hydraulic mining. A fascinating byproduct of Russia's hydraulic mining is the unearthing of thousands of woolly mammoths, many with flesh intact, locked since the **Ice** Age in frozen tundra gravel.

Stream placer deposits have their giant ancient counterparts in paleoplacers, and the Witwatersrand district in South **Africa** outproduces all others combined. Gold was reported from the Witwatersrand (White Waters Ridge) as early as 1834, but it was not until 1886 that the main deposit was discovered. From that time until today, it has occupied the paramount position in gold mining history. Witwatersrand gold was deposited between 2.9 and 2.6 billion years ago in six major fields, each produced by an ancient river system.

Placer and paleoplacers are actually secondary gold deposits, their gold having been derived from older deposits in the mountains above. The California 49ers looked upstream hoping to find the mother lode, and that's exactly what they called the system of gold veins they discovered.

Vein gold is deposited by hot subterranean water known as a hydrothermal fluid. Hydrothermal fluids circulate through rock to leach small amounts of gold from large volumes of rock and then deposit it in fractures to form veins. Major U.S. gold vein deposits have been discovered at **Lead** in the Black Hills of South Dakota and at Cripple Creek on the slopes of Pike's Peak, Colorado. Important vein deposits are also found in Canada and Australia. All these important deposits were located following the discovery of placer gold in nearby streams.

Gold's virtual indestructibility means that almost all gold ever mined could still be in use today. Today, gold is being mined in ever-increasing amounts from increasingly lower-grade deposits. It is estimated that 70% of all gold recovered has been mined in this century. Each year nearly 2,000 tons are added to the total. Nevada currently leads the nation in gold production, and the Republic of South Africa is the world's leading gold-producing nation.

Gold has traditionally been used for coinage, bullion, jewelry, and other decorative uses. Gold's chemical inertness means that gold jewelry is hypoallergenic and remains tarnish-free indefinitely.

Silver is a brilliant white metal and the best metal in terms of thermal and electrical conductivity. Its chemical symbol, Ag, is derived from its Latin name, *argentum*, meaning "shining white." Silver is not nearly as precious, dense, or noble as gold or platinum. The ease with which silverware tarnishes is an example of its chemical reactivity. Although native silver is found in nature, it most commonly occurs as compounds with other elements, especially sulfur.

Hydrothermal veins constitute the most important source of silver. The Comstock Lode, a silver bonanza 15 mi (24 km) southeast of Reno, Nevada, is a well-known example. Hydrothermal silver veins are formed in the same manner as gold veins, and the two metals commonly occur together. Silver, however, being more reactive than gold, can be leached from surface rocks and carried downward in solution. This process, called supergene enrichment, can concentrate silver into exceedingly rich deposits at depth.

Mexico has traditionally been the world's leading silver producing country, but the United States, Canada, and Peru each contribute significant amounts. Although silver has historically been considered a precious metal, industrial uses now predominate. Significant quantities are still used in jewelry, silver ware, and coinage; but even larger amounts are consumed by the photographic and electronics industries.

Platinum, like silver, is a silver-white metal. Its chemical symbol is Pt and its name comes from the Spanish world for silver (*plata*), with which it was originally confused. Its specific gravity of 21.45 exceeds that of gold, and, like gold, it is found in pure metallic chunks in stream placers. The average crustal abundance of platinum is comparable to that of gold. The **melting** point of platinum is 3,219°F (1,769°C), unusually high for a metal, and platinum is chemically inert even at high **temperature**. In addition, platinum is a catalyst for chemical reactions that produce a wide range of important commodities.

Platinum commonly occurs with five similar metals known as the platinum group metals. The group includes osmium, iridium, rhodium, palladium, and ruthenium. All were discovered in the residue left when platinum ore was dissolved in aqua regia. All are rare, expensive, and classified chemically as noble metals.

Platinum is found as native metal, in natural alloys, and in compounds with sulfur and arsenic. Platinum ore deposits are rare, highly scattered, and one deposit dominates all others much as South Africa's Witwatersrand dominates world gold production. That platinum deposit is also in the Republic of South Africa.

Placer platinum was discovered in South Africa in 1924 and subsequently traced to a distinctively layered igneous rock known as the Bushveld Complex. Although the complex is enormous, the bulk of the platinum is found in a thin layer scarcely more than three feet thick. Nearly half of the world's historic production of platinum has come from this remarkable layer.

The Stillwater complex in the Beartooth mountains of southwestern Montana also contains a layer rich in platinum group metals. Palladium is the layer's dominant metal, but platinum is also found. The layer was discovered during the 1970s, and production commenced in 1987.

Platinum is used mostly in catalytic converters for vehicular pollution control. Low-voltage electrical contracts form the second most common use for platinum, followed closely by dental and medical applications, including dental crowns, and a variety of pins and plates used internally to secure human bones. Platinum is also used as a catalyst in the manufacture of explosives, fertilizer, gasoline, insecticides, paint, plastics, and pharmaceuticals. Platinum crucibles are used to melt high-quality optical **glass** and to grow **crystals** for computer chips and lasers. Hot glass fibers for insulation and nylon fibers for textiles are extruded through platinum sieves.

Because of their rarity and unique properties, the demand for gold and platinum are expected to continue to increase. Silver is more closely tied to industry, and the demand for silver is expected to rise and fall with economic conditions.

PRECIPITATION

Precipitation is **water** in either solid or liquid form that falls from Earth's atmosphere. Major forms of precipitation include rain, snow, and hail. When air is lifted in the atmosphere, it expands and cools. Cool air cannot hold as much water in vapor form as warm air, and the **condensation** of vapor into droplets or **ice crystals** may eventually occur. If these droplets or crystals continue to grow to large sizes, they will eventually be heavy enough to fall to the earth's surface.

Precipitation in liquid form includes drizzle and raindrops. Raindrops are on the order of a millimeter (one thousandth of a meter) in radius, while drizzle drops are approximately a tenth of this size. Important solid forms of precipitation include snowflakes and hailstones. Snowflakes are formed by aggregation of solid ice crystals within a cloud, while hailstones involve supercooled water droplets and ice pellets. They are denser and more spherical than snowflakes. Other forms of solid precipitation include graupel and sleet (ice pellets). Solid precipitation may reach Earth's surface as rain if it melts as it falls. Virga is precipitation that evaporates before reaching the ground.

Precipitation forms differently depending on whether it is generated by warm or cold **clouds**. Warm clouds are defined as those that do not extend to levels where temperatures are below 32°F (0°C), while cold clouds exist at least in part at temperatures below 32°F (0°C). **Temperature** decreases with height in the lower atmosphere at a moist adiabatic rate of about 3.3°F per 3,281 ft (6°C per 1,000 m), on average. High clouds, such as cirrus, are therefore colder and more likely to contain ice. As discussed below, however, temperature is not the only important factor in the formation of precipitation.

Even the cleanest air contains aerosol particles (solid or liquid particles suspended in the air). Some of these particles are called cloud condensation nuclei, or CCN, because they provide favorable sites on which water vapor can condense. Air is defined to be fully saturated, or have a relative **humidity** of 100%, when there is no net transfer of vapor molecules between the air and a plane (flat) surface of water at the same temperature. As air cools, its relative humidity will rise to 100% or more, and molecules of water vapor will bond together, or condense, on particles suspended in the atmosphere. Condensation will preferentially occur on particles that contain water soluble (hygroscopic) material. Types of particles that commonly act as CCN include sea-salt and particles containing sulfate or nitrate ions; they are typically about 0.0000039 in (0.0001 mm) in radius. If relative humidity remains sufficiently high, CCN will grow into cloud droplets 0.00039 in (0.01 mm) or more in size. Further growth to precipitation size in warm clouds occurs as larger cloud droplets collide and coalesce (merge) with smaller ones.

Although large quantities of liquid water will freeze as the temperature drops below 32°F (0°C), cloud droplets sometimes are supercooled; that is, they may exist in liquid form at lower temperatures down to about –40°F (–40°C). At temperatures below –40°F (–40°C), even very small droplets freeze readily, but at intermediate temperatures (between –40 and 32°F or –40 and 0°C), particles called ice nuclei initiate the **freezing** of droplets. An ice nucleus may already be present within a droplet, may contact the outside of a droplet and cause it to freeze, or may aid in ice formation directly from the vapor phase. Ice nuclei are considerably more rare than cloud condensation nuclei and are not as well understood.

Once initiated, ice crystals will generally grow rapidly because air that is saturated with respect to water is supersaturated with respect to ice; i.e., water vapor will condense on an ice surface more readily than on a liquid surface. The habit, or shape, of an ice crystal is hexagonal and may be plate-like, column-like, or dendritic (similar to the snowflakes cut from paper by children). Habit depends primarily on the temperature of an ice crystal's formation. If an ice crystal grows large enough to fall through air of varying temperatures, its shape can become quite intricate. Ice crystals can also grow to large sizes by aggregation (clumping) with other types of ice crystals that are falling at different speeds. Snowflakes are formed in this way.

Clouds that contain both liquid water and ice are called mixed clouds. Supercooled water will freeze when it strikes another object. If a supercooled droplet collides with an ice crystal, it will attach itself to the crystal and freeze. Supercooled water that freezes immediately will sometimes trap air, forming opaque (rime) ice. Supercooled water that freezes slowly will form a more transparent substance called clear ice. As droplets continue to collide with ice, eventually the shape of the original crystal will be obscured beneath a dense coating of ice; this is how a hailstone is formed. Hailstones may even contain some liquid water in addition to ice. Thunderstorms are dramatic examples of vigorous mixed clouds that can produce high precipitation rates. The electrical charging of precipitation particles in thunderstorms can eventually cause **lightning** discharges.

Precipitation reaching the ground is measured in terms of precipitation rate or precipitation intensity. Precipitation intensity is the depth of precipitation reaching the ground per hour, while precipitation rate may be expressed for different time periods. Typical precipitation rates for the northeastern United States are 2–3 in (50–80 mm) per month, but in Hilo, Hawaii, 49.9 in (127 cm) of rain fell in March 1980. Average annual precipitation exceeds 80 in (200 cm) in many locations. Because snow is less compact than rain, the mass of snow in a certain depth may be equivalent to the mass of rain in only about one-tenth that depth (i.e., one inch of rain contains as much water as about 10 in [25 cm] of snow). Certain characteristics of precipitation are also measured by radar and satellites.

The earth is unique in our **solar system** in that it contains water, which is necessary to sustain life as we know it. Water that falls to the ground as precipitation is critically important to the **hydrologic cycle**, the sequence of events that moves water from the atmosphere to the earth's surface and back again. Some precipitation falls directly into the **oceans**, but precipitation that falls on land can be transported to the oceans through **rivers** or underground in aquifers. Water stored in this permeable **rock** can take thousands of years to reach the sea. Water is also contained in reservoirs such as **lakes** and the **polar ice** caps, but about 97% of the earth's water is contained in the oceans. The sun's energy heats and evaporates water from the ocean surface. On average, **evaporation** exceeds precipitation over the oceans, while precipitation exceeds evaporation over land masses. Horizontal air motions can transfer evaporated water to areas where clouds and precipitation subsequently form, completing the circle which can then begin again.

The distribution of precipitation is not uniform across the earth's surface, and varies with time of day, season and year. The lifting and cooling that produces precipitation can be caused by solar heating of the earth's surface, or by forced lifting of air over obstacles or when two different air masses converge. For these reasons, precipitation is generally heavy in the tropics and on the upwind side of tall mountain ranges. Precipitation over the oceans is heaviest at about 7°N **latitude** (the intertropical convergence zone), where the tradewinds converge and large thunderstorms frequently occur. While summer is the "wet season" for most of **Asia** and northern **Europe**, winter is the wettest time of year for Mediterranean regions and western **North America**. Precipitation is frequently associated with large-scale low-pressure systems (cyclones) at mid-latitudes.

Precipitation is obviously important to humankind as a source of drinking water and for agriculture. It cleanses the air and maintains the levels of lakes, rivers, and oceans, which are sources of food and recreation. Interestingly, human activity may influence precipitation in a number of ways, some of which are intentional, and some of which are quite unintentional. These are discussed below.

The irregular and frequently unpredictable nature of precipitation has led to a number of direct attempts to either stimulate or hinder the precipitation process for the benefit of humans. In warm clouds, large hygroscopic particles have been deliberately introduced into clouds in order to increase droplet size and the likelihood of collision and coalescence to form raindrops. In cold clouds, ice nuclei have been introduced in small quantities in order to stimulate precipitation by encouraging the growth of large ice crystals; conversely, large concentrations of ice nuclei have been used to try to reduce numbers of supercooled droplets and thereby inhibit precipitation formation. Silver iodide, which has a crystalline structure similar to that of ice, is frequently used as an ice nucleus in these "cloud seeding" experiments. Although certain of these experiments have shown promising results, the exact conditions and extent over which **cloud seeding** works and whether apparent successes are statistically significant is still a matter of debate.

Acid rain is a phenomenon that occurs when acidic pollutants are incorporated into precipitation. It has been observed extensively in the eastern United States and northern Europe. Sulfur dioxide, a gas emitted by power plants and other industries, can be converted to acidic sulfate compounds within cloud droplets. In the atmosphere, it can also be directly converted to acidic particles, which can subsequently act as CCN or be collected by falling raindrops. About 70 megatons of sulfur is emitted as a result of human activity each year across the planet. (This is comparable to the amount emitted naturally.) Also, nitrogen oxides are emitted by motor vehicles, converted to nitric acid vapor, and incorporated into clouds in the atmosphere.

Acidity is measured in terms of **pH**, the negative logarithm of the hydrogen ion concentration; the lower the pH, the greater the acidity. Water exposed to atmospheric **carbon dioxide** is naturally slightly acidic, with a pH of about 5.6. The pH of rainwater in remote areas may be as low as about 5.0 due to the presence of natural sulfate compounds in the atmosphere. Additional sulfur and nitrogen containing acids introduced by anthropogenic (human-induced) activity can increase rainwater acidity to levels that are damaging to aquatic life. Recent reductions in emissions of sulfur dioxide in the United Kingdom have resulted in partial recovery of some affected lakes.

Recent increases in anthropogenic emissions of trace gases (for example, **carbon** dioxide, methane, and chloroflourocarbons) have resulted in concern over the so-called **greenhouse effect**. These trace gases allow energy in the form of sunlight to reach the earth's surface, but "trap" or absorb the infrared energy (heat) that is emitted by the earth. The heat absorbed by the atmosphere is partially re-radiated back to the earth's surface, resulting in warming. Trends in the concentrations of these **greenhouse gases** have been used in **climate** models (computer simulations) to predict that the global average surface temperature of the earth will warm by 3.6–10.8°F (2–6°C) within the next century. For comparison, the difference in average surface temperature between the Ice Age 18,000 years ago and present day is about 9°F (5°C).

Greenhouse warming due to anthropogenic activity is predicted to have other associated consequences, including rising sea levels and changes in cloud cover and precipitation patterns around the world. For example, a reduction in summertime precipitation in the Great Plains states is predicted by many models and could adversely affect crop production. Other regions may actually receive higher amounts of precipitation than they do currently. The level of uncertainty in these model simulations is fairly high, however, due to approximations that are made. This is especially true of calculations related to aerosol particles and clouds. Also, the natural variability of the atmosphere makes verification of any current or future trends extremely difficult unless actual changes are quite large.

As discussed above, gas-phase pollutants such as sulfur dioxide can be converted into water-soluble particles in the atmosphere. Many of these particles can then act as nuclei of cloud droplet formation. Increasing the number of CCN in the atmosphere is expected to change the characteristics of clouds. For example, ships' emissions have been observed to cause an increase in the number of droplets in the marine stratus clouds above them. If a constant amount of liquid water is present in the cloud, the average droplet size will be smaller. Higher concentrations of smaller droplets reflect more sunlight, so if pollution-derived particles alter clouds over a large enough region, climate can be affected. Precipitation rates may also decrease, since droplets in these clouds are not likely to grow large enough to precipitate.

See also Air masses and fronts; Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Atmospheric pollution; Atmospheric pressure; Blizzards and lake effect snows; Clouds and cloud types; Greenhouse gases and greenhouse effect; Rainbow; Seasonal winds; Tropical cyclone; Water pollution and biological purification; Weather forecasting methods; Weather forecasting

One method of projection. © ***First Light/Corbis. Reproduced by permission.***

PROJECTION

Because the earth is a sphere, all flat maps of its surface contain inherent distortions. Map projections represent a curved land surface in two dimensions while minimizing these unavoidable errors of shape, distance, azimuth, scale and **area**. Most projections accurately portray one type of geographical information at the expense of another type, and cartographers choose a projection based on a map's intended use. A conformal projection, for example, shows relatively undistorted shapes, but inaccurate areas, while an equal-area projection makes the opposite choice. The Mercator projection is accurate at the equator but becomes progressively more distorted toward the poles, while polar stereographic maps preserve high-latitude coordinates at the expense of equatorial regions. The Mercator map of the world is responsible for the mistaken impression that Greenland covers almost as large an area as **Africa**.

The method of projecting a sphere onto a two-dimensional surface defines three classes of map projections: cylindrical, conic, and azimuthal. The alignment of the projection cylinder, cone, or plane relative to the globe further divides these classes into subtypes. Cylindrical equal-area, Mercator, Miller cylindrical, oblique Mercator, and transverse Mercator are all cylindrical map projections. Mercator maps have straight, evenly spaced lines of **latitude and longitude** that intersect at right angles, and are undistorted in scale at the equator, or at two lines of **latitude** equidistant to the equator. Mercator maps are useful for marine navigation because straight lines drawn on the map are true headings. Transverse Mercator maps are created by projecting the global sphere onto a cylinder tangent to a line of **longitude**, or meridian. The British National Grid System (BNG), used by the British Ordnance Survey, and the Universal Tranverse Mercator projection (UTM) are widely-used transverse Mercator **mapping techniques**.

Conic and azimuthal projections are less common than cylindrical projections. In a number of specific cases, however, projection of the globe onto a cone or a plane presents the most suitable map scheme. Albers equal area, equidistant conic, Lambert conformal equal area, and polyconic are all conic projections used in maps of **North America**. Most United States Geographical Survey (USGS) topographic quadrangles use a polyconic projection. Azimuthal projections are variously used for aeronautical navigation (azimuthal equidistant), maps of the ocean basins (Lambert azimuthal equal area), maps of the hemispheres (orthographic), and polar navigation (stereographic).

PROTEROZOIC ERA

The Proterozoic Era, also termed the Algonkian, is the second of the two eras into which the **Precambrian** has traditionally been divided. The Precambrian includes over four fifths of Earth's history: the 4.5 billion years from the formation of Earth to the start of the **Cambrian Period** some 570 million years ago. The first half of the Precambrian is known as the **Archean** Era and the second half as the Proterozoic Era.

Eukaryotic cells (cells with nuclei) first appeared in the early Proterozoic, about 2.5 billion years ago. Until that time only prokaryotic cells (cells without nuclei) existed. Bacteria and marine algae also evolved during the Proterozoic, and, late in the era, the first multicellular life appeared. During the Proterozoic, photosynthetic bacteria and algae liberated enough **oxygen** (O_2) from **carbon dioxide** (CO_2) to change Earth's atmosphere from oxygen-free to oxygen-rich. This chemical transformation made the Cambrian explosion of multicellular life possible.

Significant geological changes also took place during the late Archean Era and early Proterozoic Era. The continents first began to form wide, stable continental shelves at this time and to be moved about by plate-tectonic processes. On the continents, which were still devoid of plant life, **erosion** and deposition proceeded rapidly. Numerous extremely thick beds of pure **quartz sandstone** formed—some, kilometers thick. In contrast, more recently formed beds of this type are, usually, at most, 109 yards (100 meters) thick.

Throughout both the Archean Era and the Proterozoic Era, beds of the banded **iron** formation were formed. This type of banded formation consists of alternating thin layers of quartz and iron oxide and were not formed during any later period. Today they are the world's major source of iron ore.

For decades, some geologists have disputed the usefulness of the term Proterozoic (from the Greek *protero*, earlier, and *zoic*, life). The Archean-Proterozoic distinction was first devised to describe the striking unconformity (change in **rock** type with depth) that runs horizontally through the Canadian shield, a vast **area** of Precambrian rock that rings Hudson Bay and includes Greenland. However, this dramatic division has not been found globally in Precambrian rocks. Furthermore, some geologists argue that it is misleading to lump 4.5 billion years of various geological history into just two compartments. Therefore, vaguer terms—early, middle, and late (or lower, middle, and upper) Precambrian—are often used.

See also Cenozoic Era; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Origin of life; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Quaternary Period; Silurian Period; Tertiary Period

PROTONS • *see* ATOMIC THEORY

PTEROPODES • *see* CALCAREOUS OOZE

PTOLEMY (CA. 100-170)

Greek astronomer

Very little is known about Ptolemy's early life. Born in Alexandria, Egypt, as Ptolemais Hermii, his name was later latinized as Claudius Ptolemaeus, and later Ptolemy.

Ptolemy's chief contribution to science is a series of books in which he compiled the knowledge of the ancient Greeks, his primary source being Hipparchus (fl. second century B.C.). Because most of Hipparchus' writings have not survived from antiquity, many of the ideas he espoused about the universe have become known as the Ptolemaic system.

Ptolemy's system placed Earth directly at the center of the universe. The **Sun**, **Moon** and planets all orbited Earth. However, since such a scheme did not match the observed motions of the planets, Ptolemy added small orbits to the planets called *epicycles*, and introduced other mathematical devices to make a better fit.

Despite its errors and complications, the Ptolemaic system was adequate enough to make predictions of planetary positions, and it influenced thinking for 1,400 years. It was not until 1543 that Polish astronomer Nicolaus Copernicus (1473–1543) published his book refuting the Ptolemaic system. After Danish astronomer Tycho Brahe's (1546–1601) exceptionally accurate measurements of the positions of the planets showed Ptolemy's system was inaccurate, it fell upon German astronomer and mathematician **Johannes Kepler** (1571–1630) to devise a better explanation of planetary orbits.

Hipparchus had made a catalogue of stars, which were grouped into 48 constellations. Ptolemy placed them in his book and gave these patterns the names that are still in use today. He also included Hipparchus' work on trigonometry, his estimate of the distance between Earth and the Moon, which was fairly accurate, as well as Aristarchus' (third century B.C.) incorrect estimate of Earth's distance from the Sun.

Ptolemy's book was entitled *Mega (mathematike) syntaxis* ("Great [mathematical] compilation") although *Mega* was sometimes replaced by *Megiste* ("Greatest"). When the Arabs adopted the work, they called it *Al-majisti* ("The

Greatest”), which it is known as today. It was translated into Latin in 1175 (as “Almagesti” or “Almagestum”) and dominated European thinking for four centuries.

In the field of optics, Ptolemy wrote about the reflection and refraction of light. He lists tables for the refraction of light as it passes into **water** at different angles. Another book, *Tetrabiblos*, is a serious treatment of astrology.

Ptolemy also wrote a treatise that dealt with geography and included maps as well as tables of **latitude and longitude**. It explained how those lines could be mathematically determined, but only a few latitudes were calculated. He had accepted Poseidonius’ (ca. 135–51 B.C.) erroneously small estimate of the size of Earth, instead of Eratosthenes’ (ca. 276–194 B.C.) more accurate figure, and Ptolemy unwittingly may have altered the history of the world. After his geography had been translated into Latin, it eventually came to the attention of Christopher Columbus (1451–1506), who accepted the incorrect size and concluded that his search for a short-cut to **Asia** was possible.

See also History of exploration I (Ancient and classical); History of exploration II (Age of exploration)

PUMICE

Pumice is a vesicular volcanic **rock** that is commonly light enough to float in **water**. It typically has a chemical composition similar to **rhyolite** (or its plutonic counterpart, **granite**), although **magma** of virtually any composition can form pumice. The term vesicular refers to the presence of vesicles, or irregularly shaped cavities, that produce a sponge-like or bubbly texture and very low density in volcanic rocks.

Pumice can be thought of as a volcanic foam that forms when dissolved gases expand rapidly as magma rises towards the surface and confining pressure decreases. This process is similar to the foaming that occurs when a bottle of carbonated water or soda is opened. Upon eruption, the magma surrounding the gas bubbles quickly freezes into a delicate **glass** framework that produces the distinctive vesicular texture and light weight of pumice. Pumice will float if most vesicle walls remain intact and form air-filled chambers.

Reticulite is a type of pumice formed from basaltic magma in which most of the vesicle walls have burst to form a honeycomb-like structure of glassy threads. Because very few of the vesicle walls remain intact, reticulite will not float in water. Scoria, which is darker and heavier than but otherwise superficially similar to pumice, forms as a vesicular **crust** atop basaltic and andesitic **lava** flows. Close examination usually shows that scoria is much more crystalline than pumice—indicating a slower rate of cooling—and is composed of dark ferromagnesian **minerals**. It is too heavy to float in water.

The liberation of dissolved gases that produces pumice is also responsible for explosive pyroclastic eruptions. Thus, pumice fragments are commonly found within deposits of volcanic ejecta known collectively as tephra, and ash-flow deposits known as tuffs.

Pumice has a several commercial uses and is obtained from strip mines or open pit mines in volcanic rocks located throughout the western United States and elsewhere. It is most commonly used for garment softening (principally stone washed denim), as aggregate in lightweight cinder blocks and prefabricated concrete panels, as landscaping rock, as an abrasive, and as an inert filter material.

See also Andesite; Basalt; Glass; Igneous rocks; Volcanic eruptions; Volcano

Q

Quantum electrodynamics (QED)

Quantum electrodynamics (QED) is a scientific theory that is also known as the **quantum theory** of light. QED describes the quantum properties (properties that are conserved and that occur in discrete amounts called quanta) and mechanics associated with the interaction of light (i.e., electromagnetic radiation) with matter. The practical value of QED rests upon its ability, as a set of equations, to allow calculations related to the absorption and emission of light by atoms and to allow scientists to make very accurate predictions regarding the result of the interactions between photons and charged atomic particles such as electrons. QED is a fundamentally important scientific theory because it accounts for all observed physical phenomena except those associated with aspects of **relativity theory** and radioactive decay.

QED is a complex and highly mathematical theory that paints a picture of light that is counter-intuitive to everyday human experience. According to QED theory, light exists in a duality consisting of both particle and wave-like properties. More specifically, QED asserts that electromagnetism results from the quantum behavior of the photon, the fundamental "particle" responsible for the transmission electromagnetic radiation. According to QED theory, a seeming particle vacuum actually consists of electron-positron fields. An electron-positron pair (positrons are the positively charged antiparticle to electrons) comes into existence when photons interact with these fields. In turn, QED also accounts for the subsequent interactions of these electrons, positrons, and photons.

Photons, unlike other "solid" particles, are thought to be "virtual particles" constantly exchanged between charged particles such as electrons. Indeed, according to QED theory the forces of **electricity and magnetism** (i.e., the fundamental electromagnetic force) stem from the common exchange of virtual photons between particles and only under special circumstances do photons become observable as light.

According to QED theory, "virtual photons" are more like the wavelike disturbances on the surface of **water** after it is touched. The virtual photons are passed back and forth between the charged particles much like basketball players might pass a ball between them as they run down the court. As virtual particles, photons cannot be observed because they would violate the laws regarding the conservation of energy and momentum. Only in their veiled or hidden state do photons act as mediators of force between particles. The "force" caused by the exchange of virtual photons causes charged particles to change their velocity (speed and/or direction of travel) as they absorb or emit virtual photons.

Only under limited conditions do the photons escape the charged particles and thereby become observable as electromagnetic radiation. Observable photons are created by perturbations (i.e., wave-like disruptions) of electrons and other charged particles. According to QED theory, the process also works in reverse as photons can create a particle and its antiparticle (e.g., an electron and its oppositely charged antiparticle, a positron).

In QED dynamics, the simplest interactions involve only two charged particles. The application of QED is, however, not limited to these simple systems; interactions involving an infinite number of photons are described by increasingly complex processes termed second-order (or higher) processes. Although QED can account for an infinite number of processes (i.e., an infinite number of interactions) the theory also dictates that more interactions also become increasingly rare as they become increasingly complex.

The genesis of QED was the need for physicists to reconcile theories initially advanced by British physicist **James Clerk Maxwell** regarding electromagnetism in the later half of the nineteenth century (i.e., that **electricity** and **magnetism** are two aspects of a single force) with quantum theory developed during the early decades of the twentieth century. Prior to WWII, British physicist Paul Dirac, German physicist Werner Heisenberg, and Austrian-born American physicist Wolfgang Pauli all made significant contributions to the mathematical foundations related to QED. Even for these experienced physicists, however, working with QED posed formidable obstacles because of the presence of "infinities" (infinite values) in the mathematical calculations (e.g., for emission rates or determinations of mass). It was often difficult to make predictions match observed phenomena and early attempts at using QED theory often gave physicists wrong or incomprehensible answers.

The calculations used to define QED were made more accessible and reliable by a process termed renormalization, independently developed by American physicist **Richard Feynman** (1918–1988), American physicist Julian Schwinger (1918–1994), and Japanese physicist Shin'ichiro Tomonaga (1906–1979). In essence the work of these three renowned scientists concentrated on making the needed corrections to Dirac's infinity problems and his advancement of QED theory, which helped reconcile quantum mechanics with Einstein's special theory of relativity. Their "renormalization" allowed positive infinities to cancel out negative infinities and thus, allowed measured values of mass and charge to be used in QED calculations.

The use of renormalization initially allowed QED predictions to accurately predict the observed interactions of electrons and photons. During the later half of the twentieth century, based principally on the work of Feynman, Schwinger, Tomonaga and another influential physicist Freeman Dyson, QED became an important model used to explain the structure, properties and reactions of quarks, gluons and other subatomic particles. Although Feynman, Schwinger, and Tomonaga each worked separately on the refinement of different aspects of QED theory, in 1965, these physicists jointly shared the Nobel Prize for their work.

Because QED is compatible with special relativity theory, and special relativity equations are part of QED equations, QED is termed a relativistic theory. QED is also termed a gauge-invariant theory, meaning that it makes accurate predictions regardless of where applied in **space** or time. Like **gravity**, QED mathematically describes a force that becomes weaker as the distance between charged particles increases, reducing in strength as the inverse square of the distance between particles. Although the photons themselves are electrically neutral, the predictions of interactions made possible by QED would not be possible between uncharged or electrically neutral particles. Accordingly, in QED theory there are two values for electric charge on particles, positive and negative.

QED theory was revolutionary in **physics**. In contrast to theories that strove to explain natural phenomena in terms of direct causes and effects, the development of QED stemmed from a growing awareness of the limitations on scientist's ability to make predictions regarding the subatomic realm. In fact, QED was unique precisely because QED did not always make specific predictions. QED relied instead on developing an understanding of the properties and behavior of subatomic particles characterized by probabilities rather than by traditional cause-and-effect certainties. Instead of allowing scientists to make specific predictions regarding the outcome of certain interactions—Tomonaga's predictions were often mystifyingly incompatible with human experience (e.g., that an electron could be in two places at once)—QED allowed the calculation of probabilities regarding outcomes (e.g., the probability that an electron would take one path as opposed to another).

In particular, Feynman's work, teaching, and contributions to QED theory reached near legendary status within the physics community. In 1986, Feynman published *QED: The Strange Theory of Light and Matter*. In his book, Feynman attempted to explain QED theory in much the same manner as Einstein's writing on relativity theory a half century earlier. In fact, although Feynman's profound contributions to QED theory were well beyond the understanding of the general public, no other physicist since Einstein and Oppenheimer had so captured the attention of the lay public. In addition, Feynman also became somewhat of a celebrity for chronicles relating to his life and studies.

Feynman's work redefined QED theory, quantum mechanics, and electrodynamics, and Feynman's writings remain the definitive explanation of QED theory. With regard to QED theory, Feynman is perhaps best remembered for his invention of simple diagrams, now widely known among physicists as "Feynman diagrams," to portray the complex interactions of atomic particles. The diagrams allow visual representation of the ways in which particles can interact by the exchange of virtual photons. In addition to providing a tangible picture of processes outside the human capacity for observation, Feynman's diagrams precisely portray the interactions of variables used in the complex QED mathematical calculations.

Schwinger and Tomonaga also refined the mathematical methodology of QED theory so that predictions became increasingly consistent with predictions of phenomena made by the special theory of relativity. Tomonaga also solved a perplexing inconsistency that vexed Dirac's work (e.g., that an electron could, inconceivably, and not in accord with observations, be calculated to have a seemingly infinite amount of energy). Tomonaga's mathematical improvements, along with refinements made by Schwinger and Feynman, resolved this incompatibility and allowed for the calculation of finite energies for electrons. In a master-stroke, Tomonaga renormalized and made more accurate the prediction of particle properties (e.g., magnetic properties) and the process of radiation.

QED went on to become, arguably, the best tested theory in science history. Most atomic interactions are electromagnetic in nature and, no matter how accurate the equipment yet devised, the predictions made by renormalized QED theory hold true. Some tests of QED—for example, predictions of the mass of some subatomic particles—offer results accurate to six significant figures or more. Even with the improvements made by the renormalization of QED, however, the calculations often remain difficult. Although some predictions can be made using one Feynman diagram and a few pages of calculations, others may take hundreds of Feynman diagrams and the access to supercomputing facilities to complete the necessary calculations.

The development of QED theory allowed scientists to predict how subatomic particles are created or destroyed. Just as Feynman, Schwinger and Tomonaga's renormalization of QED allowed for calculation of finite properties relating to mass, energy, and charge-related properties of electrons, physicists hope that such improvements offer a model to improve other gauge theories (i.e., theories which explain how forces, such as the electroweak force, arise from underlying symmetries). The concept of forces such as electromagnetism arising from the exchange of virtual particles has intriguing ramifications for the advancement of theories regarding the working mechanisms underlying the strong, weak, and gravitational forces.

Many scientists assert that if a unified theory can be found, it will rest on the foundations established during the development of QED theory. Without speculation, however, is the fact that the development of QED theory was, and remains today, an essential element in the verification and development of quantum field theory.

See also Atomic structure; Quantum theory and mechanics

QUANTUM THEORY AND MECHANICS

Quantum mechanics describes the relationships between energy and matter on the atomic and subatomic scale. At the beginning of the twentieth century, German physicist Maxwell Planck (1858–1947) proposed that atoms absorb or emit electromagnetic radiation in bundles of energy termed quanta. This quantum concept seemed counter-intuitive to well-established Newtonian **physics**. Advancements associated with quantum mechanics (e.g., the uncertainty principle) also had profound implications with regard to the philosophical scientific arguments regarding the limitations of human knowledge.

The classical model of the **atom** evolved during the last decade of the nineteenth century and early years of the twentieth century was similar to the Copernican model of the **solar system** where, just as planets orbit the **Sun**, electrically negative electrons moved in orbits about a relatively massive, positively charged nucleus. Most importantly, in accord with Newtonian theory, the classical models allowed electrons to orbit at any distance from the nucleus. Problems with these models, however, continued to vex the leading physicist of the time. The classical models predicted that when, for example, a hydrogen atom was heated it should produce a continuous spectrum of colors as it cooled. Nineteenth century spectroscopic experiments, however, showed that hydrogen atoms produced only a portion of the spectrum. Moreover, physicist James Clerk Maxwell's (1831–1879) studies on electromagnetic radiation predicted that an electron orbiting around the nucleus according to Newton's laws would continuously lose energy and eventually fall into the nucleus.

Planck proposed that atoms absorb or emit electromagnetic radiation only in certain units or bundles of energy termed quanta. The concept that energy existed only in discrete and defined units seemed counter-intuitive, that is, outside the human experience with nature. Regardless, Planck's quantum theory, that also asserted that the energy of light was directly proportional to its frequency, proved a powerful theory that accounted for a wide range of physical phenomena. Planck's constant relates the energy of a photon with the frequency of light. Along with the constant for the speed of light, Planck's constant (h = 6.626 ù 10^{-34} Joule-second) is a fundamental constant of nature.

Prior to Planck's work, electromagnetic radiation (light) was thought to travel in waves with an infinite number of available frequencies and wavelengths. Planck's work focused on attempting to explain the limited spectrum of light emitted by hot objects and to explain the absence of what was termed the "violet catastrophe" predicted by nineteenth century theories developed by Prussian physicist Wilhelm Wien (1864–1928) and English physicist Baron (John William Strutt) Rayleigh (1842–1919).

Danish physicist **Niels Bohr** (1885–1962) studied Planck's quantum theory of radiation and worked in England with physicists J.J. Thomson (1856–1940), and Ernest Rutherford (1871–1937) improving their classical models of the atom by incorporating quantum theory. During this time, Bohr developed his model of atomic structure. To account for the observed properties of hydrogen, Bohr proposed that electrons existed only in certain orbits and that, instead of traveling between orbits, electrons made instantaneous quantum leaps or jumps between allowed orbits. According to the **Bohr model**, when an electron is excited by energy it jumps from its ground state to an excited state (i.e., a higher energy orbital). The excited atom can then emit energy only in certain (quantized) amounts as its electrons jump back to lower energy orbits located closer to the nucleus. This excess energy is emitted in quanta of electromagnetic radiation (photons of light) that have exactly same energy as the difference in energy between the orbits jumped by the electron.

The electron quantum leaps between orbits proposed by the Bohr model accounted for Plank's observations that atoms emit or absorb electromagnetic radiation in quanta. Bohr's model also explained many important properties of the photoelectric effect described by **Albert Einstein** (1879–1955).

The development of quantum mechanics during the first half of the twentieth century replaced classical Copernican-like atomic models of the atom. Using probability theory, and allowing for a wave-particle duality, quantum mechanics also replaced classical mechanics as the method by which to describe interactions between subatomic particles. Quantum mechanics replaced electron "orbitals" of classical atomic models with allowable values for angular momentum (angular velocity multiplied by mass) and depicted electrons position in terms of probability "clouds" and regions.

When Planck started his studies in physics, Newtonian or classical physics seemed fully explained. In fact, Planck's graduate advisor once claimed that there was essentially nothing new to discover in physics. By 1918, however, the importance of the quantum mechanics was recognized and Planck received the Nobel Prize in physics. The philosophical implications to quantum theory seemed so staggering, however, that Planck himself admitted that he did not fully understand the theory. In fact, Planck initially regarded the development of quantum mechanics as a mathematical aberration or temporary answer to be used only until a more intuitive or common-sense model was developed.

Despite Planck's reservations, however, Einstein's subsequent Nobel Prize winning work on the photoelectric effect was heavily based on Planck's theory. Expanding on Planck's explanation of blackbody radiation, Einstein assumed that light was transmitted in as a stream of particles termed photons. By extending the well-known wave properties of light to include a treatment of light as a stream of photons, Einstein was able to explain the photoelectric effect.

The Bohr model of atomic structure was published in 1913, and Bohr's work earned a Nobel Prize in 1922. Bohr's model of the hydrogen atom proved to be insufficiently complex to account for the fine detail of the observed spectral lines. Prussian physicist Arnold (Johannes Wilhelm) Sommerfeld's (1868–1951) refinements (e.g., the application of elliptical, multi-angular orbits), however, explained the fine structure of the observed spectral lines.

Later in the 1920s, the concept of quantization and its application to physical phenomena was further advanced by more mathematically complex models based on the work of the French physicist Louis Victor de Broglie (1892–1987) and Austrian physicist **Erwin Schrödinger** (1887–1961) that depicted the particle and wave nature of electrons. De Broglie showed that the electron was not merely a particle but a waveform. This proposal led Schrödinger to publish his wave equation in 1926. Schrödinger's work described electrons as "standing wave" surrounding the nucleus and his system of quantum mechanics is called wave mechanics. German physicist Max Born (1882–1970) and English physicist P. A. M. Dirac (1902–1984) made further advances in defining the subatomic particles (principally the electron) as a wave rather than as a particle and in reconciling portions of quantum theory with **relativity theory**.

Working at about the same time, German physicist Werner Heisenberg (1901–1976) formulated the first complete and self-consistent theory of quantum mechanics. Matrix mathematics was well established by the 1920s, and Heisenberg applied this powerful tool to quantum mechanics. In 1926, Heisenberg put forward his uncertainty principle that states that two complementary properties of a system, such as position and momentum, can never both be known exactly. This proposition helped cement the dual nature of particles (e.g., light can be described as having both wave and particle characteristics). Electromagnetic radiation (one region of the spectrum of which comprises visible light) is now understood as having both particle and wave-like properties.

In 1925, Austrian-born physicist Wolfgang Pauli (1900–1958) published the Pauli exclusion principle that states that no two electrons in an atom can simultaneously occupy the same quantum state (i.e., energy state). Pauli's specification of spin (+½ or –½) on an electron gave the two electrons in any suborbital differing quantum numbers (a system used to describe the quantum state) and made completely understandable the structure of the **periodic table** in terms of electron configurations (i.e., the energy related arrangement of electrons in energy shells and suborbitals).

In 1931, American chemist Linus Pauling published a paper that used quantum mechanics to explain how two electrons, from two different atoms, are shared to make a covalent bond between the two atoms. Pauling's work provided the connection needed in order to fully apply the new quantum theory to chemical reactions.

Quantum mechanics posed profound questions for scientists and philosophers. The concept that particles such as electrons making quantum leaps from one orbit to another, as opposed to simply moving between orbits, seems counter-intuitive. Like much of quantum theory, the proofs of how nature works at the atomic level are mathematical. Bohr himself remarked, "Anyone who is not shocked by quantum theory has not understood it."

The rise of the importance and power of quantum mechanics carried important philosophical consequences. When misapplied to larger systems—as in the famous paradox of Schrödinger's cat—quantum mechanics was often misinterpreted to make bizarre predictions (i.e., a cat that is simultaneously dead and alive). On the other hand, quantum mechanics made possible important advances in cosmological theory.

Quantum and relativity theories strengthened philosophical concepts of complementarity, wherein phenomena can be looked upon in mutually exclusive yet equally valid perspectives. In addition, because of the complexity of quantum relationships, the rise of quantum mechanics fueled a holistic approach to explanations of physical phenomena. Following the advent of quantum mechanics, the universe could no longer be explained in terms of Newtonian causality but only in terms of statistical, mathematical constructs.

In particular, Heisenberg's uncertainty principle asserts that knowledge of natural phenomena is fundamentally limited—to know one part allows another to move beyond recognition. Quantum mechanics, particularly in the work of Heisenberg and Schrödinger, also asserted a indeterminist (no preferred frame of reference) epistemology (study of the nature and limits of human knowledge).

Fundamental contradictions to long-accepted Newtonian causal and deterministic theories made even the leading scientists of the day resistant to the philosophical implications of quantum theory. Einstein argued against the seeming randomness of quantum mechanics by asserting, "God does not play dice!" Bohr and others defended quantum theory with the gentle rebuttal that one should not "prescribe to God how He should run the world."

See also Atomic structure; Quantum electrodynamics (QED)

QUARTZ

Quartz (SiO_2), a common mineral, is the product of the two most prevalent elements in the earth's **crust**: **silicon** and **oxygen**. Quartz can be found as giant **crystals** or small grains, and is the main component of most types of **sand**. It is the hardest common mineral, and for this reason is often used in the making of sandpaper, grindstones, polishers, and industrial cleaners. Though quartz is clear and glassy in its large crystal form, called **rock** quartz, it also can be found in several shades of coloration, the most familiar being rose quartz (pink), smoky quartz (brown), and amethyst (purple).

Rose quartz. ***U.S. National Aeronautics and Space Administration (NASA).***

Quartz has a variety of scientific and industrial uses, chiefly because it possesses piezoelectricity. Discovered by the French physicist and chemist **Pierre Curie** (1859–1906), the piezoelectric effect is a phenomenon demonstrated by certain crystals: when squeezed or stretched, a voltage is produced across the crystal's face. This effect is reversible as well, for when a voltage is applied to a piezoelectric crystal it will stretch; if the polarity of the voltage is alternated, the crystal will rapidly expand and contract, producing a vibration. It is this vibration that makes quartz especially useful. Every kind of piezoelectric crystal has a natural vibration frequency that is determined by its thickness—the thinner the crystal, the higher the frequency. When a crystal is made to vibrate at its natural frequency by the application of a voltage, the system is said to be in resonance. A crystal in resonance will maintain a constant, unfaltering frequency. When coupled with vacuum tubes or transistors, this constant frequency can be changed into a radio signal. Such was the design of the quartz radio, used primarily during World War II. Another common use of quartz is in timekeeping. All clocks rely upon some form of oscillator to keep regular time; for example, mechanical clocks sometimes use a pendulum to regulate the motion of their hands. In a quartz timepiece, a small ring-shaped piece of crystal is made to vibrate at its natural frequency. A microchip reads how many times the quartz vibrates each second and uses that information to keep accurate time. Because the crystal's vibration is unfaltering, quartz clocks are among the most precise timekeeping devices, losing less than one hundred thousandth of a second each day. Quartz crystals can be used to regulate both digital and analog clocks and watches.

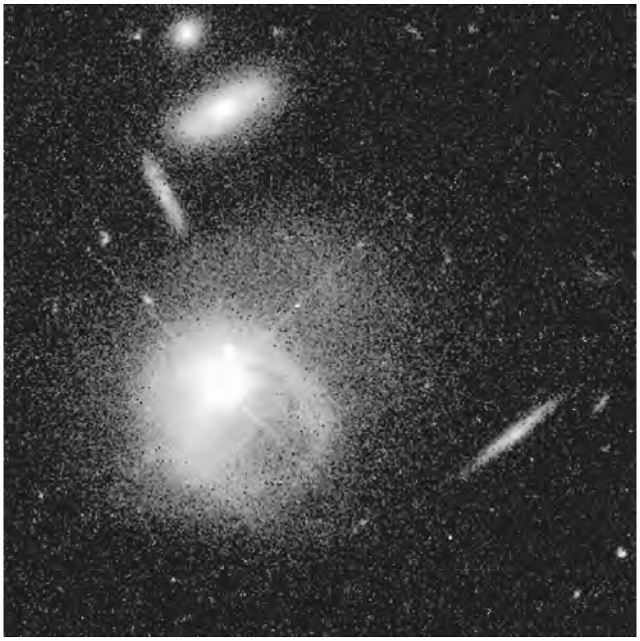
Because of the many applications for quartz, the demand for clear, flawless rock crystal is often greater than the supply. Shortly after World War II, scientists developed a process by which quartz can be "grown" in the laboratory. Scientists begin with a small piece of natural crystal called a seed. Placing the seed within an alkaline solution, along with a supply of silica, they apply heat and pressure to the mixture. Slowly, the silica bonds with the seeds, eventually forming large, near-perfect crystals. Another type of man-made quartz, called fused quartz, is made by **melting** down many pieces of natural quartz and reforming it into almost any shape. Fused quartz displays many useful properties not found in natural quartz. First, because it neither expands nor contracts with changing temperatures, it makes an ideal component of precise scientific equipment, such as **telescope** and microscope lenses. It also is an unsurpassed conductor of heat, light, and **ultraviolet rays**, and in many cases it can be used to direct light rays through bends and angles. Additionally, fused quartz, which is nearly impervious to acids and other chemicals, is often used to make test tubes and other chemical containers.

See also Industrial minerals

QUASARS

Quasi-stellar radio sources (quasars) are the most distant cosmic objects observed by astronomers. Although not visible to the naked eye, quasars are also among the most energetic of cosmic phenomena. Even though some quasars may be physically smaller in size than our own **solar system**, some quasars are calculated to be brighter than hundreds of galaxies combined. Quasars and active galaxies appear to be related phenomena, each associated with massive rotating black holes in their central region. As a type of active galaxy, the enormous energy output of quasars can be explained using the theory of general relativity.

The great distance of quasars means that the light observed coming from them was produced when the universe was very young. Because of the finite speed of light, large cosmic distances translate to looking back in time. The observation of quasars at large distances and of their nearby scarcity argues that quasars were much more common in the early universe. Correspondingly, quasars may also represent the earliest stages of galactic **evolution**. This change in the universe over time (e.g., specifically the rate of quasar formation) contradicted steady-state cosmological models that relied on a universe that was the same in all directions (when averaged



Quasar PKS. Quasars are highly energetic objects billions of light years away, and some of the oldest objects in the known universe. ***U.S. National Aeronautics and Space Administration (NASA).***

over a large span of **space**) and at all times. Along with the discovery of ubiquitous cosmic background radiation, the discovery of quasars tilted the cosmological argument in favor of Big Bang based cosmological models.

In 1932, American engineer Karl Jansky (1905–1945) discovered the existence of radio waves emanating from beyond the solar system. By the mid-1950s, an increasing number of astronomers using radio telescopes sought explanations for mysterious radio emissions from optically dim stellar sources.

In 1962, British radio astronomer Cyril Hazard used the **moon** as an occultive shield to discover strong radio emissions traceable to the constellation Virgo. Optical telescopes pinpointed a faint star-like object (subsequently designated quasar 3C273—3rd Cambridge Catalog, 273rd radio source) as the source of the emissions. Of greater interest was an unusual emission spectrum found associated with 3C273. In 1963, American astronomer Marten Schmidt explained the abnormal spectrum from 3C273 as evidence of a highly redshifted spectrum. Redshift describes the Doppler-like shift of spectral emission lines toward longer (hence, redder) wavelengths in objects moving away from an observer. Observers measure the light coming from objects moving away from them as redshifted (i.e., at longer wavelengths and at a lower frequency when the light was emitted). Conversely, observers measure the light coming from objects moving toward them as blueshifted (i.e., at shorter wavelengths and at a higher frequency when the light was emitted). Most importantly, the determination of the amount of an object's redshift allows the calculation of a recession velocity. Moreover, because the recession rate increases with distance, the recession velocity is a function (known as the Hubble relation) of the distance to the receding object. After 3C273, many other quasars were discovered with similarly redshifted spectra.

Schmidt's calculation of the redshift of the 3C273 spectrum meant that 3C273 was approximately three billion light-years away from Earth. It became immediately apparent that, if 3C273 was so distant, it had to be many thousands of times more luminous than a normal galaxy for the light to appear as bright as it did from such a great distance. Refined calculations involving the luminosity of 3C273 indicate that, although dim to optical astronomers, the quasar is actually five trillion times as bright as the **Sun**. The high redshift of 3C273 also implied a great velocity of recession measuring one-tenth the speed of light.

Astronomers now assert that quasars represent a class of galaxies with extremely energetic centers. Large radio emissions seem most likely associated with massive black holes with great amounts of matter available to enter the accretion disk. In fact, prior to more direct observations late in the twentieth century, the discovery of quasars provided at least tacit proof of the existence of black holes. Black holes form around a singularity (the remnant of a collapsed massive star) with a gravitational field so intense that not even light can escape. Located outside the black hole is the accretion disk, an **area** of intense radiation emitted as matter heats and accelerates toward the black hole's event horizon (the boundary past which nothing can escape). Further, as electrons in the accretion disk are accelerated to near light speed, they are influenced by a strong **magnetic field** to emit quasar-like radio waves in a process termed synchrotron radiation. Electromagnetic waves similar to the electromagnetic waves emanating from quasars are observed on Earth when physicists pass high-energy electrons through synchrotron particle accelerators. Studies of Quasar 3C273 and other quasars identified jets of radiation blasting tens of thousands of light-years into space.

In addition to radio and visible light emissions, some quasars emit light in other regions of the **electromagnetic spectrum** including ultraviolet, infrared, x ray, and gamma-ray regions. In 1979, an x-ray quasar was found to have a redshift of 3.2, indicating a recession velocity equaling 97% the speed of light.

Not all quasars or active galaxies are alike. Although they seem optically similar to energetic quasars, at least 90% of active galaxies appear to be radio quiet. Accordingly, Seyfert galaxies or quasi-stellar objects (QSO) may be radio silent or emit electromagnetic radiation at greatly reduced levels. More than 1,500 quasars have now been identified as distant QSO. One hypothesis accounts for these quiet quasars by linking them to smaller black holes, or to black holes in regions of space with less matter available for consumption.

The limitations of ground-based telescopes and the need to study quasars was officially cited as one of the principal reasons to build the **Hubble Space Telescope** launched by the United States in 1990. In addition to direct studies of quasars, astronomers use quasars as an electromagnetic backdrop that can be used to study the primitive gas **clouds** found in the early universe.

See also Big bang theory; Stellar life cycle

QUATERNARY PERIOD

In **geologic time**, the Quaternary Period (also termed the Anthropogene Period), the second geologic period in the **Cenozoic Era**, spans the time between roughly 2.6 million years ago (mya) and present day. On the geologic time scale, Earth is currently in the Quaternary Period of the Cenezoic Era of the **Phanerozoic Eon**.

The Quaternary Period contains two geologic epochs. The earliest epoch, the **Pleistocene Epoch** ranges from approximately 2.6 mya to 10,000 years ago. The Pleistocene Epoch is further subdivided into (from earliest to most recent) Gelasian and Calabrian stages. The Calabrian stage is also frequently replaced by a series of geologic stages, from earliest to most recent, including the Danau, Donau-Günz, Günzian, Günz-Mindel, Mindelian, Mindel-Riss, Rissian, Riss-Würm, and Würmian stages. The latest, most recent, and current epoch, the **Holocene Epoch** ranges from approximately 10,000 years ago until present day. According to geologic time, Earth is currently in the Holocene Epoch.

During the Quaternary Period, Earth's continents assumed their modern configuration. The Pacific Ocean separated **Asia** and **Australia** from **North America** and **South America**; the Atlantic Ocean separated North and South America from **Europe** (Euro-Asia) and **Africa**. The Indian Ocean filled the basin between Africa, India, Asia, and Australia. The Arabian Plate wedged between the Eurasian and African plates continues to provide high levels of tectonic activity (e.g., earthquakes) in the **area** of modern day Turkey. The Indian plate driving against and under the Eurasian plate uplifts both in rapid mountain building. As a result of the ongoing collision, ancient oceanic **crust** bearing marine fossils was uplifted into the Himalayan chain. The collision between the Indian and Eurasian plate continues with a resulting slow—but measurable—increase in the altitude of the highest Himalayan mountains (e.g., Mt. Everest) each year.

Glaciation (e.g., **ice ages**), and fluctuating climatic conditions—possibly at least partially explainable by Milankovitch cycles—during both the Tertiary and Quaternary Periods brought about sweeping changes in the landscape evident in modern topographical features.

The **fossil record** provides evidence that by the end of the **Tertiary Period** (also known as the Neogene period), the species *Ardipithecus ramidus* walked upright in an area now encompassing modern Ethiopa. Near the start of the Quaternary Period, a number of species lived and became extinct before modern humankind (*Homo sapiens*) appeared. Many of these species, including *Australopithecus anamensis*, *Australopithecus afarensis*, *Australopithecus garhi*, and *Australopithecus africanus* were only collateral rungs on the ladder of **evolution** to *Homo sapiens,* and do not provide a direct evolutionary link to humans. Although these species became extinct near the start of the Quaternary Period, they at least co-existed with the direct ancestors of humans. Early in the Quaternary Period *Homo habilis* and *Homo rudolfensis* lived and became extinct. Their extinctions are dated to approximately the appearance of *Homo ergaster*, a species some anthropologists argue is one of the earliest identifiable direct ancestors of *Homo erectus*, *Homo heidelbergensis*, *Homo neanderthalensis*, and *Homo sapiens*.

The last major **impact crater** with a diameter over 31 mi (50 km) struck Earth near what is now Kara-Kul, Tajikistan at the **Pliocene Epoch** and Pleistocene Epoch geologic time boundary that established the start of the Quaternary Period.

See also Archean; Cambrian Period; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Historical geology; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Precambrian; Proterozoic Era; Silurian Period; Supercontinents; Triassic Period

R

RADAR AND SONAR

Although they rely on two fundamentally different types of wave transmission, Radio Detection and Ranging (RADAR) and Sound Navigation and Ranging (SONAR) both are **remote sensing** systems with important military, scientific and commercial applications. RADAR sends out electromagnetic waves, while active SONAR transmits acoustic (i.e., sound) waves. In both systems, these waves return echoes from certain features or targets that allow the determination of important properties and attributes of the target (i.e., shape, size, speed, distance, etc.). Because electromagnetic waves are strongly attenuated (diminished) in **water**, RADAR signals are mostly used for ground or atmospheric observations. Because SONAR signals easily penetrate water, they are ideal for navigation and measurement under water.

The threat of submarine warfare during World War I made urgent the development of SONAR and other means of echo detection. The development of the acoustic transducer that converted electrical energy to sound waves enabled the rapid advances in SONAR design and technology during the last years of the war. Although active SONAR was developed too late to be useful during World War I, the push for its development reaped enormous technological dividends. Not all of the advances, however, were restricted to military use. After the war, echo sounding devices were placed aboard many large French ocean-liners.

During the early battles of World War II, the British Anti-Submarine Detection and Investigation Committee (its acronym, ASDIC, became a name commonly applied to British SONAR systems) made efforts to outfit every ship in the British fleet with advanced detection devices. The use of ASDIC proved pivotal in the British effort to repel damaging attacks by German submarines upon both British warships and merchant ships keeping the island nation supplied with munitions and food.

While early twentieth century SONAR developments proceeded, another system of remote sensing was developed based upon the improved understanding of the nature and propagation of electromagnetic radiation achieved by Scottish physicist **James Clerk Maxwell** (1831–1879) during the 19th century. Scottish physicist and meteorologist Sir Robert Alexander Watson-Watt (1892–1973) successfully used short-wave radio transmissions to detect the direction of approaching thunderstorms. Another technique used by Watson-Watt and his colleagues at the British Radio Research Station measured the altitude of the **ionosphere** (a layer in the upper atmosphere that can act as a radio reflector) by sending brief pulses of radio waves upward and then measuring the time it took for the signals to return to the station. Because the speed of radio waves was well established, the measurements provided very accurate determinations of the height of the reflective layer. In 1935, Watson-Watt had the ingenious idea of combining these direction and range finding techniques and, in so doing, he invented RADAR. Watson-Watt built his first practical RADAR device at Ditton Park.

Shortly thereafter, without benefit of a test run, Watson-Watt and Ministry scientists conducted an experiment to test the viability of RADAR. Watson-Watt's apparatus was found able to illuminate (i.e., detect) aircraft at a distance of up to eight miles. Within a year, Watson-Watt improved his RADAR systems so that it could detect aircraft at distances up to seventy miles. Pre-war Britain quickly put Watson-Watt's invention to military use and by the end of 1938, primitive RADAR systems dotted the English coast. These stations, able to detect aircraft regardless of ground fogs or **clouds**, were to play an important role in the detection of approaching Nazi aircraft during World War II. By the end of the war, the British and American forces had developed a number of RADAR types and applications including air interception (AI), air-to-surface vessel (ASV), ground controlled interception (GCI), and various gun sighting and tracking RADARs.

Regardless of their application, both RADAR and SONAR targets scatter, deflect, and reflect incoming waves. This scattering is, however, not uniform, and in most cases a strong echo of the image is propagated back to the signal

RADAR and SONAR allow ships to safely operate in conditions where vision is either not possible or feasible. ***AP/Wide World. Reproduced by permission.***

transmitter in much the same way as a smooth mirror can reflect light back in the specular direction. The strength of the return signal is also characteristic of the target and the environment in which the systems are operating. Because they are electromagnetic radiations, RADAR waves travel through the atmosphere at the speed of light (in air). SONAR waves (compression waves) travel through water at much slower pace, the speed of sound. By measuring the time it takes for the signals to travel to the target and to return echoes, both RADAR and SONAR systems are capable of accurately determining the distance to their targets.

Within their respective domains, both RADAR and SONAR can operate reliably under a wide variety of adverse conditions to extend human sensing capabilities.

RADAR technology also had a dramatic impact on the fledgling science of radio **astronomy**. During the Second World War, British officer, J.S. Hey correctly determined that the **Sun** was a powerful source of radio transmissions. Hay discovered this while investigating the causes of system wide jamming of the British RADAR net that could not be attributed to enemy activity (Hey attributed the radio emission to increased solar flare activity). Although kept secret during the war, British RADAR installations and technology became the forerunners of modern radio telescopes as they recorded celestial background noise while listening for the telltale signs of enemy activity.

Remote sensing tools such as RADAR and SONAR also allow scientists, geologists, and archaeologists to map **topography** and subsurface features on Earth and on objects within the **solar system**. SONAR readings led to advances in underwater seismography that allowed the mapping of the ocean floors and the identification of mineral and energy resources.

See also Sound transmission

RADIATION FOG • *see* FOG

RADIOACTIVE DECAY • *see* DATING METHODS

RADIOACTIVE WASTE STORAGE (GEOLOGIC CONSIDERATIONS)

In the 1960s, nuclear power gained popularity as a means of producing power for civilian use. During the next two decades, several nuclear power plants were built, but there was little consensus about how to best dispose of radioactive waste. Waste from plants, as well as from military and defense operations, was usually stored on site or in nearby storage facilities. Low-level waste, such as that from hospitals, research labs, and power plants is generally placed into containment facilities on-site. However, the disposal of high-level waste, materials that are highly radioactive, remains more problematic. Spent nuclear **fuels** from power plants are sometimes shipped to containment facilities, and sometimes stored in specially constructed containment pools on-site. Radioactive waste is thus, stored in various locations, governed by federal regulations. Forty-three states in the United States, and several Canadian provinces, currently have nuclear waste storage facilities. In the late 1990s, the government proposed plans for a central storage facility for high-level waste at Yucca Mountain, Nevada. In May, 2002, the United States House of Representatives approved a measure that would establish the site at Yucca Mountain, and in July 2002, the United States Senate approved the site for development, following 20 years of debate in Congress. The Yucca Mountain site has sparked ongoing controversy over the environmental impact of nuclear waste storage, much of which focuses on the unique geological and environmental conditions of the region.

When looking for a site for permanent storage of high level waste, engineers and geologists took several factors into consideration, including: **water table**, geological stability, **rock** composition, seismic (**earthquake**) activity, and proximity to population areas. Furthermore, the site must have a high probability of remaining undisturbed for tens of thousands of years, or as long as the materials in storage are radioactive. Yucca Mountain is located in a rural region, with sparse population. Las Vegas, 100 mi (161 km) from the site, is the nearest metropolitan **area**. Within a 100-mi radius of the proposed site, there are approximately 35,000 inhabitants. Thus, Yucca Mountain is relatively secluded.

Yucca Mountain itself has a **desert climate**, receiving less than six inches of rain per year. The lack of rain means that **cave** systems within the mountain are dry, and that there is minute seepage from the surface of the mountain to the deep **water** table 2000 ft (670 m) below ground. This ensures that waste stored in the mountain would have fewer chances of polluting ground water if specially engineered storage containers ever rupture. The deep location of the water table at the site also means that the cavity, or storage room, would lie equidistant from the surface of the mountain to ground water stores—about 1000 ft, or 304 m. This isolates the waste, and removes the chance of accidental disturbance from future drilling or other means of exploration.

Some aspects of the geological composition of the mountain itself further makes Yucca Mountain a candidate for a nuclear waste repository. Dense volcanic rock, as well as thick and nearly impenetrable **bedrock** mean the Yucca Mountain's interior is relatively stable, not very porous, and resistant to water and heat. Under the most extreme conditions, this deep and solid rock could help contain minor seepage, as well as insulate the repository—possibly making it as safe as a band of untapped uranium ore.

Yucca Mountain's unique **geology** and environment is unequaled by that of any of the nation's other current nuclear waste repositories, many of which pose a greater potential threat to cities, drinking water, and their local environments. Centralization could potentially lead to tighter regulation of waste, better handling, and less environmental damage.

While Yucca Mountain does meet much of the criteria for a safe storage site, it is not a perfect location. The region around Yucca Mountain contains several **faults and fractures** (cracks in the Earth's **crust** where movement causes earthquakes), and is considered seismically active. Earthquakes could change the patterns of water flow inside the mountain, and well as endanger the integrity of the storage cavities within the mountain. Increased hydrothermal activity could promote seepage and water contamination.

Researchers also explored the possibility of the storage cavity filling with water, thus exposing the **aquifer** and **groundwater** to radioactive contaminants. Geologists studied core samples and cave linings to determine the extent to which **minerals** permeated the walls of the cavities. The scientists found that there were only scant traces of opal and calcite, telltale signs of flooding and water seepage, at the lower levels of the mountain. Thus, the cavities did not have a history of filling with water. A corresponding study of the geological history of the mountain further confirmed the relative stability of the site's water table, drainage, and seepage.

However, under Yucca Mountain is a deep aquifer. In the desert region, the aquifer provides drinking and irrigation water. As metropolitan centers, such as Las Vegas, continue to grow, the aquifer might play a significant role as a water resource for the region. The nuclear storage site would have to remain stable and well sealed for tens of thousands of years in order to ensure the continued safety of the aquifer.

Part of the problem in designing high-level waste storage facilities is the time span for which these sites must remain secure and safe. Lab tests are inadequate to insure the stability of the mountain, the fortitude of containers and casks, and the security of the site from accidental intrusion for the tens of thousands of years necessary for radioactive waste to be rendered harmless. Project planners face not only design difficulties such as preventing accidents and mitigating environmental impact, but also how to document the site in ways that will ensure that people 10,000 years from now will recognize the hidden danger of the mountain storage facility. People today have only scant artifacts and generalized understanding of civilizations and people that lived ten thousand years ago.

Geologists and other scientists disagree on the possible effect that the waste could have on the behavior of the mountain itself. Some predict that heat generated by the waste could alter the mountain's geological and hydrological behavior, causing rocks to crack and water to seep into and out of the storage cavity in ways that we cannot predict. Some raise concerns over the unpredictable nature of seismic activity in the area. Other scientists assert that the stable pattern of geological processes at Yucca Mountain will remain unchanged, and that the site is predictably stable. Geologists have to account for not only the mountain's history, but also predict its future in order to insure the safety of the site for future generations.

While much of the scientific community's assessment of the safety of the Yucca Mountain project centers on geology, public concerns focus on technology. Though waste is currently stored in forty-three states, little of the nation's spent nuclear materials travel long distances. The creation of the Yucca Mountain site would require that waste be shipped by truck and rail to the central storage facility. Engineers and researchers have developed safe casks, or storage bins, which are impervious to accidents, water, and fire specifically for shipping high-level waste, but may people are discomforted simply by the perceived risk (the threat that people feel is associated with a given project, not the statistical risk) of shipping nuclear materials.

The controversy surrounding the Yucca Mountain waste repository is both political and scientific. The perceived threat of nuclear materials heavily influences public opinion, and environmentalists are reticent to trade many smaller environmental problems for a large potential hazard. Some people cite the Yucca Mountain facility as a means of centralizing the problem of nuclear waste. Project proponents claim that the repository will lessen environmental risk and keep volatile, dangerous materials secure and controlled. The scientific community is also in discord over the geological impact of the project, thus exposing the many unknown variables that **Earth science** still has not defined.

See also Radioactivity; Water pollution and biological purification; Water table

RADIOACTIVITY

Radioactivity originates from extraterrestrial sources and terrestrial geologic sources. All elements with more than 83 protons (i.e., an **atomic number** greater than 83) are radioactive. Some radioactive isotopes also occur in elements with lower atomic numbers.

Atoms that are radioactive emit radioactivity during spontaneous transformation from an unstable isotope to a more stable one. Natural radioactive decay provides a source of heating in Earth's interior that drives mantle dynamics and **plate tectonics**. Both natural and man-made sources of radioactivity at certain levels may represent a significant health risk to humans and other organisms. Radioactive materials must be isolated from the environment until their radiation level has decreased to a safe level, a process which requires thousands of years for some materials.

Radiation is classified as being ionizing or nonionizing. Both types can be harmful to humans and other organisms. Nonionizing radiation is relatively long-wavelength electromagnetic radiation, such as radio waves, microwaves, visible radiation, ultraviolet radiation, and very low-energy electromagnetic fields. Nonionizing radiation is generally considered less dangerous than ionizing radiation. However, some forms of nonionizing radiation, such as ultraviolet radiation, can damage biological molecules and cause health problems. Scientists do not yet fully understand the longer-term health effects of some forms of nonionizing radiation, such as that from very low-level electromagnetic fields (e.g., high-voltage power lines), although the evidence to date suggests that the risks are extremely small.

Ionizing radiation is the short wavelength radiation or particulate radiation emitted by certain unstable isotopes during radioactive decay. There are about 70 radioactive isotopes, all of which emit some form of ionizing radiation as they decay. A radioactive isotope typically decays through a series of intermediate isotopes until it reaches a stable isotope state. As indicated by its name, ionizing radiation can ionize the atoms or molecules with which it interacts. In other words, ionizing radiation can cause other atoms to release their electrons. These free electrons can damage many biochemicals, such as proteins, lipids, and nucleic acids (including DNA). In intense radioactivity, this damage can cause severe human health problems, including cancers, and death.

Ionizing radiation can be either short-wavelength electromagnetic radiation or particulate radiation. Gamma radiation and x radiation are short-wavelength electromagnetic radiation. Alpha particles, beta particles, neutrons, and protons are particulate radiation. Alpha particles, beta particles, and gamma rays are the most commonly encountered forms of radioactive pollution. Alpha particles are simply ionized helium nuclei, and consist of two protons and two neutrons. Beta particles are electrons, which have a negative charge. Gamma radiation is high-energy electromagnetic radiation.

Scientists have devised various units for measuring radioactivity. A Curie (Ci) represents the rate of radioactive decay. One Curie is 3.7×10^{10} radioactive disintegrations per second. A rad is a unit representing the absorbed dose of radioactivity. One rad is equal to an absorbed energy dose of 100 ergs per gram of radiated medium. A rem is a unit that measures the effectiveness of radioactivity in causing biological damage. One rem is equal to one rad times a biological weighting factor. The weighting factor is 1.0 for gamma radiation and beta particles, and it is 20 for alpha particles. The radioactive **half-life** is a measure of the persistence of radioactive material. The half-life is the time required for one-half of an initial quantity of atoms of a radioactive isotope to decay to a different isotope.

In the United States, people are typically exposed to about 350 millirems of ionizing radiation per year. On average, 82% of this radiation comes from natural sources and 18% from anthropogenic sources (i.e., those associated with human activities). The major natural source of radiation is radon gas, which accounts for about 55% of the total radiation dose. The principal anthropogenic sources of radioactivity are medical x rays and nuclear medicine. Radioactivity from the fallout of nuclear weapons testing and from nuclear power plants make up less than 0.5% of the total radiation dose, i.e., less than 2 millirems. Although the contribution to the total human radiation dose is extremely small, radioactive isotopes released during previous atmospheric testing of nuclear weapons will remain in the atmosphere at detectable levels for the next 100 to 1000 years.

People who live in certain regions are exposed to higher doses of radiation. For example, residents of the Rocky Mountains of Colorado receive about 30 millirems more cosmic radiation than people living at sea level. This is because the atmosphere is thinner at higher elevations, and therefore less effective at shielding the surface from cosmic radiation. Exposure to cosmic radiation is also high while people are flying in an airplane, so pilots and flight attendants have an enhanced, occupational exposure. In addition, residents of certain regions receive higher doses of radiation from radon-222, due to local geological anomalies. Radon-222 is a colorless and odorless gas that results from the decay of naturally occurring, radioactive isotopes of uranium. Radon-222 typically enters buildings from their ground level.

Personal lifestyle also influences the amount of radioactivity to which people are exposed. For example, miners, who spend a lot of time underground, are exposed to relatively high doses of radon-222 and consequently have relatively high rates of lung cancer. Cigarette smokers expose their lungs to high levels of radiation, because tobacco plants contain trace quantities of polonium-210, lead-210, and radon-222. These radioactive isotopes come from the small amount of uranium present in fertilizers used to promote tobacco growth. Consequently, the lungs of a cigarette smoker are exposed to thousands of additional millirems of radioactivity, although any associated hazards are much less than those of tar and nicotine.

The U.S. Nuclear Regulatory Commission has strict requirements regarding the amount of radioactivity that can be released from a nuclear power reactor. In particular, a nuclear reactor can expose an individual who lives on the fence line of the power plant to no more than 10 millirems of radiation per year. Actual measurements at U.S. nuclear power plants have shown that a person who lived at the fence line would actually be exposed to much less than 10 millirems.

Thus, for a typical person who is exposed to about 350 millirems of radiation per year from all other sources, much of which is natural background, the proportion of radiation from nuclear power plants is extremely small. In fact, **coal-** and oil-fired power plants, which release small amounts of radioactivity contained in their **fuels**, are responsible for more airborne radioactive pollution in the United States than are nuclear power plants.

By far, the worst nuclear reactor accident occurred in 1986 in Chernobyl, Ukraine. An uncontrolled build-up of heat resulted in a meltdown of the reactor core and combustion of **graphite** moderator material in one of the several generating units at Chernobyl, releasing more than 50 million Curies of radioactivity to the ambient environment. The disaster killed 31 workers and resulted in the hospitalization of more than 500 other people from radiation sickness. According to Ukrainian authorities, during the decade following the Chernobyl disaster an estimated 10,000 people in Belarus, Russia, and Ukraine died from cancers and other radiation-related diseases caused by the accident. In addition to these relatively local effects, the atmosphere transported radioactive fallout from Chernobyl into **Europe** and throughout the Northern Hemisphere.

Geiger counters are used to detect subatomic particles emitted by radioactive substances. ***Hank Morgan. National Audubon Society Collection/Photo Researchers, Inc. Reproduced by permission.***

The large amount of radioactive waste generated by nuclear power plants is another important problem. This waste will remain radioactive for many thousands of years, so technologists must design systems for extremely long-term storage. One obvious problem is that the long-term reliability of the storage systems cannot be fully assured, because they cannot be directly tested for the length of time they will be used (i.e., for thousands of years). Another problem with nuclear waste is that it will remain extremely dangerous for much longer than the expected lifetimes of existing governments and social institutions. Thus, future societies of the following millennia, however they may be structured, will be responsible for the safe storage of nuclear waste that is being generated today.

See also Atmospheric chemistry; Atmospheric pollution; Atomic mass and weight; Atomic theory; Atoms; Atomic theory; Carbon dating; Cosmic microwave background radiation; Environmental pollution; Geochemistry; Radioactive waste storage (geological considerations); Radon production, detection and elimination; Ultraviolet rays and radiation

RADIOMETRIC DATING • *see* DATING METHODS

RADON PRODUCTION, DETECTION, AND ELIMINATION

Radon (usually in the form of the Radon-222 isotope) is a colorless and odorless radioactive gas formed from radioactive decay. The most common geologic source of radon derives from the decay of uranium. Radon is commonly found at low levels in widely dispersed crustal formations, **soil**, and **water** samples. To some extent, radon can be detected throughout the United States. Specific geologic formations, however, frequently present elevated concentration of radon that may pose a significant health risk. The Surgeon General of the United States and the Environmental Protection Agency identify radon exposure as the second leading cause of lung cancer in the United States. Cancer risk rates are based upon magnitude and duration of exposure.

Produced underground, radon moves toward the surface and eventually diffuses into the atmosphere or in **groundwater**. Because radon has a **half-life** of approximately four days, half of any size sample deteriorates during that time. Regardless, because radon can be continually supplied, dangerous levels can accumulate in poorly ventilated spaces (e.g., underneath homes, buildings, etc.). Moreover, the deterioration of radon produces alpha particle radiation and radioactive decay products that can exhibit high surface adherence to dust particles. Radon detection tests are designed to detect radon gas in picocuries per liter of air (pCi/L). The picocurie is used to measure the magnitude of radiation in terms of disintegrations per minute. One pCi, one trillionth of a Curie, translates to 2.2 disintegrations per minute. EPA guidelines recommend remedial action (e.g., improved ventilation) if long term radon concentrations exceed 4 pCi/L.

Working level units (WL) are used to measure radon decay product levels. The working level unit is used to measure combined alpha radiation from all radon decay products. Commercial test kits designed for use by the general public are widely available. The most common forms include the use of charcoal canisters, alpha track detectors, liquid scintillation detectors, and ion chamber detectors. In most cases, these devices are allowed to measure cumulative radon and byproduct concentrations over a specific period of time (e.g., 60–90 days) that depends on the type of test and geographic radon risk levels. The tests are usually designed to be returned to a qualified laboratory for analysis.

The EPA estimates that nearly one out 15 homes in the United States has elevated radon levels.

Radon can be kept at low concentration levels by ventilation and the use of impermeable sheeting to prevent radon seepage into enclosed spaces. Radon in water does not pose nearly the health risk as does breathable radon gas. Regardless, radon removal protocols are increasingly a part of water treatment programs. Radon is removed from water by aeration or **carbon** filtration systems.

Exposure to radon is cumulative. Researchers are presently conducting extensive research into better profiling the mutagenic risks of long term, low-level radiation exposure.

See also Atmospheric pollution; Atomic theory; Atoms; Cosmic microwave background radiation; Environmental pollution; Radioactivity

RAIN • *see* PRECIPITATION

RAINBOW

Water droplets and light form the basis of all rainbows, which are circular arcs of color with a common center. Because only water and light are required for rainbows, one will see them in rain, spray, or even **fog**.

A raindrop acts like a prism and separates sunlight into its individual color components through refraction, as light will do when it passes from one medium to another. When the white light of the **Sun** strikes the surface of the raindrop, the light waves are bent to varying degrees depending on their wavelength. These wavelengths are reflected on the far surface of the water drop and will bend again as they exit. If the light reflects off the droplet only once, a single rainbow occurs. If the rays bounce inside and reflect twice, two rainbows will appear: a primary and a secondary. The second one will appear fainter because there is less light energy present. It will also occur at a higher angle.

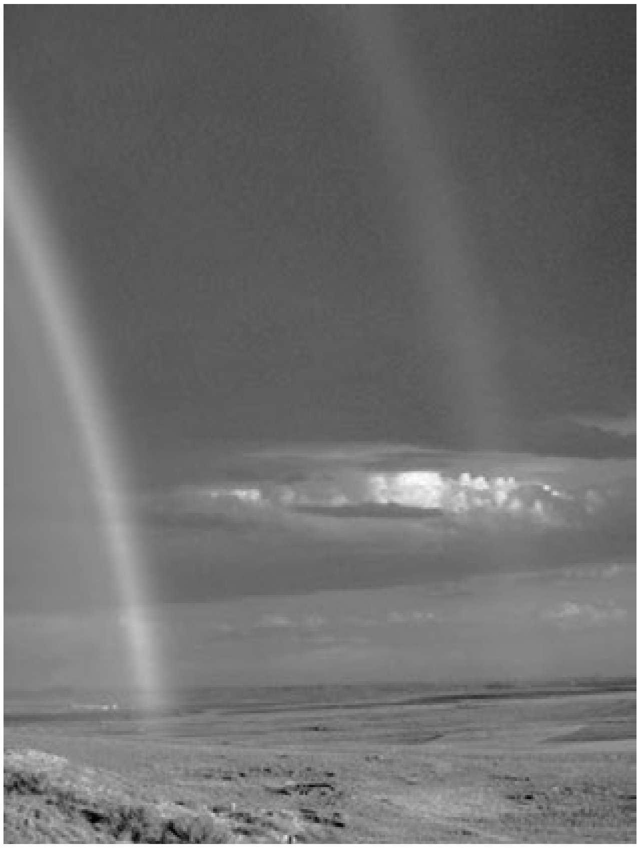
Not all the light that enters the raindrop will form a rainbow. Some of the light, that which hits the droplet directly at its center, will simply pass through the other side. The rays that strike the extreme lower portions of the drop will produce the secondary bow, and those that enter at the top will produce the primary bow.

The formation of the arc was first discussed by Rene Descartes in 1637. He calculated the deviation for a ray of red light to be about 138 degrees. Although light rays may exit the drop in more than one direction, a concentration of rays emerges near the minimum deviation from the direction of the incoming rays. Therefore the viewer sees the highest intensity looking at the rays that have minimum deviation, which form a cone with the vertex in the observer’s eye and with the axis passing through the Sun.

The color sequence of the rainbow is also due to refraction. It was **Sir Isaac Newton**, however, 30 years after Descartes, who discovered that white light was made up of different wavelengths. Red light, with the longest wavelength, bends the least, while violet, being the shortest wavelength, bends the most. The vertical angle above the horizon will be a little less than 41° for the violet (about 40°) and a little more for the red (about 42°). The secondary rainbow has an angular radius of about 50° and its color sequence is reversed from the primary. It is universally accepted that there are seven rainbow colors, which appear in the order: red, orange, yellow, green, blue, indigo, and violet. However, the rainbow is a whole continuum of colors from red to violet and even beyond the colors that the eye can see.

Supernumerary rainbows, faintly colored rings just inside of the primary bow, occur due to interference effects on the light rays emerging from the water droplet after one internal reflection.

No two people will see the same rainbow. If one imagines herself or himself standing at the center of a cone cut in half lengthwise and laid on the ground flatside down, the raindrops that bend and reflect the sunlight that reach the person’s eye as a rainbow are located on the surface of the cone. A viewer standing next to the first sees a rainbow generated by a different set of raindrops along the surface of a different imaging cone.



A double rainbow over the desert. *FMA. Reproduced by permission.*

Using the concept of an imaginary cone again, a viewer could predict where a rainbow will appear by standing with his back to the sun and holding the cone to his eye so that the extension of the axis of the cone intersects the Sun. The rainbow will appear along the surface of the cone as the circular arc of the rainbow is always in the direction opposite to that of the Sun.

A rainbow lasts only about a half-hour because the conditions that create it rarely stay steady much longer than this. In many locations, spring is the prime rainbow-viewing month. Rainfall is usually more localized in the spring, and brief showers over limited areas are a regular feature of atmospheric behavior. This change is a result of the higher springtime sun warming the ground more effectively than it did throughout the previous winter months. This process produces local convection. These brief, irregular periods of **precipitation** followed by sunshine are ideal rainbow conditions. Also, the Sun is low enough for much of the day to allow a rainbow to appear above the horizon—the lower the sun, the higher the top of a rainbow.

The “purity” or brightness of the colors of the rainbow depends on the size of the raindrops. Large drops or those with diameters of a few millimeters create bright rainbows with well-defined colors; small droplets with diameters of about 0.01 mm produce rainbows of overlapping colors that appear nearly white.

For refraction to occur, the light must intersect the raindrops at an angle. Therefore no rainbows are seen at noon when the sun is directly overhead. Rainbows are more frequently seen in the afternoon because most showers occur in midday rather than morning. Because the horizon blocks the other half of a rainbow, a full 360° rainbow can only be viewed from an airplane.

The sky inside the arc will appear brighter than that surrounding it because of the number of rays emerging from a raindrop at angles smaller that those that are visible. But there is essentially no light from single internal reflections at angles greater than those of the rainbow rays. In addition to the fact that there is a great deal of light directed within the arc of the bow and very little beyond it, this light is white because it is a mixture of all the wavelengths that entered the raindrop. This is just the opposite in the case of a secondary rainbow, where the rainbow ray is the smallest angle and there are many rays that emerge at angles greater than this one. A dark band forms where the primary and secondary bows combine. This is known as the Alexander’s Dark Band, in honor of Alexander of Aphrodisias who discovered this around 200 B.C.

If a viewer had a pair of polarizing sunglasses, he or she would see that light from the rainbow is polarized. Light vibrating horizontally at the top of the bow is much more intense than the light vibrating perpendicularly to it across the bow and it may be as much as 20 times as strong.

Although rare, a full **moon** can produce a lunar rainbow when it is bright enough to have its light refracted by raindrops just as is the case for the Sun.

See also Electromagnetic spectrum

RAINFOREST • *see* FORESTS AND DEFORESTATION

RAPIDS AND WATERFALLS

Rapids are stream sections with extremely strong currents, numerous obstacles, and steps in their streambeds. A waterfall is a vertical drop in a streambed. Both are sites of vigorous **erosion**. Rapids often form where resistant **bedrock** confines a stream to a narrow channel, and forces an increase in **water** velocity. Fast-moving water, laden with abrasive **sand** and gravel, cuts into the bedrock, forming cliffs on either side of the cataract. Large boulders fall from the cliffs, creating obstacles in the streambed, and increasing water turbulence. Rapids are navigational hazards that have hampered exploration, travel, and trade on the world’s **rivers** throughout human history. Today, adventurers explore remote natural areas, and test their athletic abilities, by kayaking, canoeing, and rafting along these treacherous stretches of rivers.

Waterfalls form where fast-flowing water traverses a geologic contact between more resistant and less resistant **rock** layers, or across a fault that has juxtaposed different rock types. In other words, waterfalls often form at the end of a

Victoria Falls, bordering with Zimbabwe and Zambia. ***Cynthia Bassett. Reproduced by permission.***

series of rapids. (The classic movie scene in which the protagonists survive a trip through rapids only to be carried over a waterfall contains an element of reality.) Turbulent, sediment-laden water quickly erodes the less-resistant rocks, creating a vertical step in the streambed. Falling water erodes the soft rock even more quickly, and the waterfall grows taller. Turbulence at the base of the waterfall undercuts the newly-formed cliff, and it moves upstream. Niagara Falls, for example, retreats upstream about 3.3 ft (1 m) each year. Waterfalls also form where streams flow across pre-existing cliffs. They are common where streams reach the ocean along eroding or tectonically uplifting coastlines. For example, many streams end at spectacular waterfalls along the Scandinavian **fjords**. Yosemite Valley's famous waterfalls occur where small streams flow over the rim of the valley. Angel Falls, in Venezuela, is Earth's tallest waterfall at 3212 ft (979 m). Victoria Falls, on the Zambizi River along the border of Zambia and Zimbabwe, is one of the natural wonders of world; its beauty and mythical history are legendary.

See also Bed or traction load; Stream valleys, channels and floodplains

RATE FACTORS IN GEOLOGIC PROCESSES

The rates at which geologic processes occur range from imperceptibly slow to exceptionally fast.

At the slow end of the spectrum, mountain ranges rise, basins subside, and tectonic plates move over time periods that span many millions of years. Recent research using repeated **GPS** (global positioning **satellite**) measurements of crustal deformation has shown, for example, that the Los Angeles basin is being shortened at a rate that is on the order of a few millimeters per year as the result of movement along faults throughout the basin. Likewise, the rate at which the earth's **crust** rebounds after the retreat of continental **glaciers** is generally on the order of a few millimeters per year and decreases with time. Measurements of offset strata cut by faults, combined with radiometric age dating, also suggest that crustal deformation rates are on the order of millimeters per year.

At the opposite end of the spectrum, acoustic waves traveling through **rock** (for example, from earthquakes, blasting, or seismic exploration surveys) typically travel at velocities of one to ten thousand meters per second. Thus, an observer standing 62 mi (100 km) from the epicenter of a large

earthquake may have to wait 10 or 20 seconds before ground shaking begins. The catastrophic debris **avalanche** that occurred in conjunction with the 1980 eruption of Mount St. Helens traveled at a velocity greater than 149 mph (240 kph), which is fast in terms of human perception but is on the order of one-millionth of the velocity of typical seismic waves.

The rate at which any given geologic process occurs can vary significantly. Different kinds of landslides, for example, can move at rates as slow as a few centimeters per year to rates as rapid as tens of meters per second, a range that extends over eight orders of magnitude. Similarly, the flow of **groundwater** through porous aquifers is controlled by a combination of the hydraulic gradient and the **permeability** of the **aquifer**, which can vary over many orders of magnitude. In general, however, groundwater and other subsurface fluids generally flow at velocities so low that their kinetic energy (proportional to the square of the velocity) can safely be ignored in calculations. The viscosity, or resistance to flow, of fluids such as **lava** and crude oil depend strongly on the **temperature** and chemical composition of the fluid. For example, the viscosity of **basalt** lava falls by a factor of 100 to 1,000 as its temperature increases from 2,100°F to 2,550°F (1,150°C to 1,400°C). Therefore basalt lava, which is typical of Hawaiian volcanoes, flows as easily as honey (honey at room temperature has the same viscosity as basalt at 2,550°F/1,400°C) when it first erupts but slows and eventually solidifies in place as it cools. The rates of chemical reactions, for example those associated with **metamorphism** and ore deposit formation, are also strongly dependent upon pressure and temperature.

The rates at which rocks are subjected to stress can also control their response. A rock struck sharply with a hammer will behave as a brittle substance, deforming elastically and, if the blow is strong enough, breaking into pieces. Earthquakes are an example of naturally occurring elastic deformation of rocks. Over the lengths of time required to build mountain ranges, however, rocks appear to deform as very viscous fluids via a process known as slow creeping flow. The viscosity of deforming rocks is also influenced by pressure and temperature conditions during mountain building episodes.

Geologic process rates must also be viewed in relationship to the rates at which society functions. In many parts of the world, for example, groundwater pumping rates exceed those at which aquifers are naturally replenished, resulting in land subsidence that can occur at the rate of tens of centimeters per year. Humans have also become significant geologic agents and are responsible for the movement of 37 billion tons of **soil** and rock per year throughout the world. Likewise, the rates at which mineral and energy resources are consumed by society need to be balanced by the rates at which humans discover new deposits and develop new technologies for extraction, as well as the extremely slow rates at which mineral and energy resources accumulate over **geologic time**.

See also Catastrophism; Half-life; Historical geology; Uniformitarianism

RAY, JOHN (1627-1705)

English naturalist

A predecessor of Carl Linnaeus, John Ray was the first naturalist to use the idea of species to distinguish different organisms from each other. Focusing primarily on the classification of plants and basing his system on the work of Aristotle, Ray divided plants into two groups: the moncotyledons and the dicotyledons. Both are still recognized today. In 1693, Ray published the final volume of *Histora Plantarum,* a complete classification of plants and one of the first natural systems of classification that was based on physical characteristics rather than origin and perceived use.

John Ray was born in Black Notley, Essex, England, to Roger Ray, a blacksmith, and Elizabeth Ray, an amateur herbalist and medical practitioner. He attended Trinity College at Cambridge from 1644–1651, receiving both a bachelor and masters degree. After graduation, he continued at Trinity as an appointed fellow of the college. He taught a number of courses, including Greek, mathematics, and humanities. Ray left his post at Trinity during the Reformation, when he refused to sign an oath required by the Act of Uniformity in 1662. It was at this time that his contribution to taxonomy flourished.

Without employment, Ray relied on the patronage of former students. One such patron was Francis Willughby, a wealthy contemporary from Cambridge. With the support of Willughby, Ray was able to expand his classification of plants from a part-time endeavor restricted to the indigenous species of Chambridgeshire to the whole of the British Isles and beyond. Willughby accompanied Ray on his many expeditions, and his interest in animals complimented Ray's own interests in plants. Ray's collaboration with Willughby ended in 1672, with the death of Willughby. That same year, Ray married Margaret Oakeley. They settled in Black Notley, where Ray continued his scientific endeavors.

As part of his work, Ray was able to convincingly show that **fossils** represented extinct species. At the time, the link between fossils and extinct species was not an accepted model; however, Ray's evidence provided the basis for the formation of a more thorough system of paleontology. Such a view was unusual for a naturalist at this time, particularly considering Ray's strong religious beliefs.

John Ray never lost his love and wonder for nature and had no problem reconciling his views of the world with his views of religion. As well as publishing extensively on natural history, Ray also published many theological works, including *The Wisdom of God*, and he was only stopped from taking priestly orders by the English civil war and Reformation. According to Ray, the study of nature was a way to reveal the omnipotence of God and to be a naturalist was a way to work within divinity.

See also Fossil record; Fossils and fossilization; History of exploration II (Age of exploration)

Red tides are caused by a population explosion of microorganisms called dinoflagellates. The seawater becomes toxic to most life, and kills fish in the area. ***AP/Wide World. Reproduced by permission.***

RED TIDE

Red tide is a condition in which a huge **area** of seawater turns to a reddish-brown hue. This rusty-red discoloration is caused by an exploding population of tiny single-celled microorganisms called dinoflagellates, which are usually found in ocean **water**, but occasionally in **lakes** and **rivers** as well. Red **tides** have occurred naturally since **oceans** were formed, but today they are becoming more common because of human influence. During summer months, the warm **Sun** and an abundance of food in the water create optimal conditions for the breeding of dinoflagellates, which are a type of phytoplankton. This multiplication, or bloom, happens rapidly, and the seawater becomes extremely dense with dinoflagellates; sometimes their numbers can reach many millions per cup of seawater. Even though most red tides are harmless, many of them are toxic and extremely dangerous to fish, shellfish, birds, and even humans. Certain species of dinoflagellates are capable of producing highly-toxic substances.

When these toxic red tides appear in warm coastal places like Texas and Florida, people are warned not to swim, fish, or eat locally-caught fish. Clams, oysters, mussels, and other shellfish are especially dangerous because they feed on the dinoflagellates and retain the toxins. If ingested by humans, contaminated shellfish can cause nausea and diarrhea or worse. In severe cases, the poisons attack human muscle fibers and can cause partial paralysis or even death. In addition to being warned not to eat or catch fish, people are generally advised to stay away from coastal areas during red tide. Decaying bodies of dead fish and birds can create foul smells in the air. Moreover, when people inhale the air around windblown red tide, their lungs can become irritated.

Today, red tides are increasingly common in the **Gulf of Mexico**. Many rivers, including the Mississippi, empty into the Gulf, depositing sewage, industrial waste, and chemicals into the ocean. These pollutants contain phosphorous and nitrogen which then serve as food for the dinoflagellate algae. As the algae organisms consume the nitrogen and phosphorous, they spread their color across the water, cutting off sunlight and **oxygen** to other marine life. The severity of red tide is unpredictable because of such factors as the **weather**, water composition, marine life, and pollution levels. Red tides can last for a few hours or up to several months. The size can range from less than a few square yards to more than 1,000 miles (1613 km).

See also Environmental pollution; Oceans and seas; Water pollution

REGOLITH

Regolith is a layer of loose or unlithified **soil** and **rock** debris that overlies and blankets **bedrock**. It is derived from the Greek roots *rhegos*, for blanket, and *lithos*, for stone. The term is descriptive and non-genetic, meaning that regolith refers to any blanket of unlithified material regardless of its origin. Lunar regolith (also known as lunar soil) is the loose material ranging in size from dust to boulders on the surface of the **Moon**, and is believed to have been formed as a result of meteorite impact and fragmentation.

Regolith can be transported by a variety of geologic processes or formed in place by the chemical and physical **weathering** of bedrock. Transported regolith can include volcanic ash, glacial deposits, alluvium, colluvium (debris accumulating near the base of a slope due to **creep** or related processes), talus, loess (windblown silt), eolian deposits, **landslide** and **debris flow** deposits, and soil. Regolith resting on slopes can also be the source material for landslides, debris flows, and rock falls. Because regolith can be the product of many different geological processes, its physical characteristics (for example, density, **permeability**, **porosity**, and strength) can be highly variable over short distances. Geologic maps typically do not portray regolith unless it is so thick that it completely obscures bedrock or the purpose of the map is specifically to show unlithified surficial deposits.

In the fields of engineering **geology**, geotechnical engineering, and soil mechanics, regolith is often referred to as soil even though it may not have been altered by biological and chemical soil forming processes. These conflicting definitions of soil can cause confusion, so it is always important to understand the context in which the word is being used.

Characterization of the physical properties of regolith is of paramount importance in many engineering and environmental projects. In some cases, regolith must be removed in order to construct foundations on bedrock. In other cases, it is the regolith itself in which structures are anchored or which constitutes the source of material for embankments and other earthworks. Regolith can also be a locally significant **aquifer** that yields **groundwater** relatively easily and inexpensively. Because regolith lies at the earth's surface, however, aquifers in it are much more easily polluted than those in deeper **artesian** aquifers.

See also Alluvial system; Eolian processes; Glacial landforms; Landscape evolution; Soil and soil horizons; Stream valleys, channels, and floodplains; Talus pile or Talus slope

RELATIVE AGE • *see* DATING METHODS

RELATIVE HUMIDITY • *see* HUMIDITY

RELATIVITY THEORY

Relativity theory, a general term encompassing special and general relativity theories, sets forth a specific set of laws relating motion to mass, **space**, time, and **gravity**. Relativity theory allows calculations of the differences in mass, space, and time as measured in different reference frames.

At the start of the twentieth century the classical laws of **physics** contained in Sir Isaac Newton's (1642–1727) 1687 work, *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)* adequately described the phenomena of everyday existence. In accord with these laws, more than century of experimental and mathematical work in **electricity and magnetism** resulted in Scottish physicist James Clerk Maxwell's (1831–1879) four equations describing light as an electromagnetic wave. Prior to Maxwell's equations it was thought that all waves required a medium or ether for propagation. Such an ether would also serve as an absolute reference frame against which absolute motion, space and time could be measured. Ironically, although Maxwell's equations established that electromagnetic waves do not require such a medium, Maxwell and others remained unconvinced and the search for an elusive ether continued. For more than three decades, the lack of definable or demonstrable ether was explained away as simply a problem of experimental accuracy. The absence of a need for an ether for the propagation of electromagnetic radiation was demonstrated in late nineteenth century experiments conducted by Albert Michelson (1852–1931) and Edward Morley (1838–1923).

In 1904, French mathematician Jules-Henri Poincaré (1854–1912) pointed out important problems with concepts of simultaneity by asserting that observers in different reference frames must measure time differently. In 1905, a German-born clerk in the Swiss patent office named **Albert Einstein** (1879–1955) published a theory of light that incorporated implications of Maxwell's equations, demonstrated the lack of need for an ether, explained FitzGerald-Lorentz contractions, and explained Poincaré's reservations concerning differential time measurement. Both Einstein and his special relativity theory went to revolutionize modern physics.

In formulating his special theory of relativity, Einstein assumed that the laws of physics are the same in all inertial (moving) reference frames and that the speed of light was measured as a constant regardless of its direction of propagation. Moreover, the measured speed of light was independent of the velocity of the observer.

Einstein's special theory of relativity also related mass and energy. Einstein published a formula relating mass and energy, $E=mc^2$ (Energy=mass times speed of light squared). Einstein's equation implied that tremendous energies were contained in small masses. Along with advancements in **atomic theory**, Einstein's insights ultimately allowed the development of atomic weapons during World War II and the dawn of the nuclear age.

Special relativity also gave rise to a number of counterintuitive paradoxes dealing with the passage of time (e.g., the twin paradox) and with problems dependent upon an assumption of simultaneity. According to the postulates of special relativity, under certain conditions it would be impossible to determine when one event happened in relation to another event.

Although Einstein's special theory was limited to special cases dealing with systems in uniform nonaccelerated motion, the theory did away with the need for an absolute frame of reference. In addition, the implications of special relativity on the equivalence of mass and energy revolutionized classical laws regarding conservation of mass and energy. A more complete understanding of the conservation of mass and energy now relies upon mass-energy systems. Einstein's special relativity theory was also important in the development of **quantum theory**. German Physicist **Max Planck** (1858–1947) and others who were in the process of developing quantum theory, set out to reconcile (often unsuccessfully) relativity theory with quantum theory.

In 1915, a decade after publishing his special relativity theory, Einstein published his general theory of relativity that soon came to supplant well-understood Newtonian concepts of gravity. Although Newtonian theories of gravity hold valid for most objects, there were small but noticeable errors in calculations regarding the motion of bodies at high velocities or for description of motion in massive gravitational fields. These small errors were completely corrected by the general theory of relativity that described nonuniform, or accelerated, motion.

General relativity's impact on calculations regarding gravity sparked dramatic revisions in **cosmology** that continue today. The conceptual fusion of traditional three-dimensional space with time to create space-time also made observers more integral to measurement of phenomena.

In a sophisticated elaboration of Newton's laws of motion, in general relativity theory the motion of bodies is explained by the assertion that in the vicinity of mass, space-time curves. The more massive the body the greater the curvature of space-time and, consequently, the greater the force of gravitational attraction.

It may be fairly argued that the most stunning philosophical consequence of general relativity was that space-time is a creation of the universe itself. Under general relativity, the universe is not simply expanding into preexisting space and time, but rather creating space-time as a consequence of expansion. In this regard, general relativity theory set the stage for the subsequent development of **Big Bang theory**.

Unlike the esoteric proofs of special relativity, the proofs of general relativity could be measured by conventional experimentation. General relativity's assertion that gravitational fields would bend light was confirmed during a 1919 solar **eclipse**. Other predictions regarding shifts in the perihelion of Mercury and in redshifted spectra also found confirmation. Using relativity based equations, German physicist Karl Schwarzschild (1873–1916) mathematically described the gravitational field near massive compact objects. Schwarzschild's work subsequently enabled the predication and discovery of the evolutionary stages in massive stars (e.g., neutron stars, black holes, etc.).

Relativity theory was quickly accepted by the general scientific community, and its implications on general philosophical thought were profound. Although Newtonian physics still enjoys widespread utility, along with quantum physics, relativity-based theories have replaced Newtonian cosmological concepts.

See also Astronomy; Cosmic microwave background radiation; Cosmology

RELIC DUNES • *see* DUNES

RELIEF

Relief is the difference in altitude between the highest and lowest point of a defined **area** (Relief = highest point – lowest point).

Although to humans the earth is composed of towering mountains and deep **ocean trenches**, Earth's relief, when compared to its overall size, is very small. From a not too distant point in **space**, the earth appears essentially smooth.

For example, using sea level as a base, in 1999 Mt. Everest—the highest point on Earth—measured slightly over 29,000 ft (8,850 m) above sea level. The Marinas Trench, at an estimated depth of 37,000 ft (11,300 m) below sea level (approximately 7 mi, or 11.2 km), is the lowest point on Earth. Using these approximate figures, the relief of Earth is then calculated to be an estimated 66,000 ft (20,117 m). [66,000= 29,000 ft – –37,000 ft (minus 37,000 ft because the reference point of 0 is assigned to sea level)]

The "smooth" character of the earth is fairly argued when comparing the scant 12.5-mi (20.1-km) relief of Earth's surface with Earth's approximate 7,900-mile (12,714-km) diameter. The relief measures less than two-tenths of one percent of the overall size of the earth.

Topographic maps depict elevation and contours (lines of equal elevation) show the progression of surface altitude changes. Relief is a critical component when defining certain area geographic features. For example, a plateau is a broad area with steep sided uplifts but with low relief on the surface. Correspondingly, a basin is often described as a low-lying area with low relief.

Although relief generally changes with geologic slowness (e.g., the uplift of Mt. Everest), relief in some **desert** areas—highly exposed to **wind** forces—often shows dramatic and rapid changes.

See also Cartography; GIS; Landforms; Landscape evolution; Topography and topographic maps

REMOTE SENSING

Remote sensing is the science and art of obtaining and interpreting information about an object, **area**, or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area, or phenomenon being observed. There are four major characteristics of a remote sensing system, namely, an electromagnetic energy source, transmission path, target, and sensor.

The **Sun** is a common source of electromagnetic energy. It radiates **solar energy** in all directions. Earth reflects the energy from the Sun and emits some energy in the form of heat.

Based on the energy source, remote sensing systems can be grouped into two types, passive and active systems. Passive remote sensing systems detect radiation that is reflected and/or emitted from the surface features of Earth. Examples are the Landsat and European SPOT **satellite** systems. Active remote sensing systems provide their own energy source. For example, the Radarsat-1 synthetic aperture radar (SAR) system has an antenna that beams pulses of electromagnetic energy towards the target.

The transmission path is the **space** between the electromagnetic energy source and the target, and back to the sensor. In the case of Earth observation, the transmission path is usually the atmosphere of Earth. While passing through Earth's atmosphere, the electromagnetic energy can be scattered by minute particles or absorbed by gases such that its strength and spectral characteristics are modified before being detected by the sensor.

The target could be a particular object, an area, or phenomenon. For example, it could be a ship, city, forest cover, mineralized zone, and **water** body contaminated by oil slick, a forest fire, or a combination thereof.

Electromagnetic energy that hits a target, called incident radiation, interacts with matter or the target in several ways. The energy could be reflected, absorbed, or transmitted. When incident radiation hits a smooth surface, it is reflected or bounced in the opposite direction like light bouncing off a mirror. If it hits a relatively rough surface, it could be scattered in all directions in a diffuse manner. When incident radiation is absorbed, it loses its energy largely to heating the matter. A portion of the energy may be emitted by the heated substance, usually at longer wavelengths. When incident radiation is transmitted, it passes through the substance such as from air into water.

The sensor is a device that detects reflected and/or emitted energy. Passive remote sensing systems carry optical sensors that detect energy in the visible, infrared, and thermal infrared regions of the **electromagnetic spectrum**. Common sensors used are cameras and charge-coupled detectors (**CCD**) mounted on either airborne or space-borne platforms. In active remote sensing systems, the same antenna that sends out energy pulses detects the return pulse.

Present applications of remote sensing are numerous and varied. They include land cover mapping and analysis, land use mapping, agricultural plant health monitoring and harvest forecast, water resources, wildlife ecology, archeological investigations, snow and **ice** monitoring, disaster management, geologic and **soil** mapping, mineral exploration, coastal resource management, military surveillance, and many more.

One main advantage of a remote sensing system is its ability to provide a synoptic view of a wide area in a single frame. The width of a single frame, or swath width, could be 37 mi x 37 mi (60 km x 60 km) in the case of the European

SPOT satellite, or as wide as 115 mi x 115 mi (185 km x 185 km) in the case of Landsat. Remote sensing systems can provide data and information in areas where access is difficult as rendered by terrain, **weather**, or military security. The towering Himalayas and the bitterly cold Antarctic regions provide good examples of these harsh environments. Active remote sensing systems provide cloud-free images that are available in all weather conditions, day or night. Such systems are particularly useful in tropical countries where constant cloud cover may obscure the target area. In 2002, the United States military initiatives in Afghanistan used remote sensing systems to monitor troops and vehicle convoy movements at spatial resolutions of less than one meter to a few meters. Spatial resolution or ground resolution is a measure of how small an object on Earth's surface can be "seen" by a sensor as separate from its surroundings.

The greater advantage of remote sensing systems is the capability of integrating multiple, interrelated data sources and analysis procedures. This could be a multistage sensing wherein data on a particular site is collected from the multiple sources at different altitudes like from a low altitude aircraft, a high altitude craft, a **space shuttle** and a satellite. It could also be a multispectral sensing wherein data on the same site are acquired in different spectral bands. Landsat-5, for example, acquires data simultaneously in seven wavelength ranges of the electromagnetic spectrum. Or, it could be a multitemporal sensing whereby data are collected on the same site at different dates. For example, data may be collected on rice-growing land at various stages of the crop's growth, or on a **volcano** before and after a volcanic eruption.

Two satellite systems in use today are the Landsat and Radarsat remote sensing systems. Landsat is the series of Earth observation satellites launched by the U.S. National Aeronautics and Space Administration (NASA) under the Landsat Program in 1972 to the present. The first satellite, originally named Earth Resources Technology Satellite-1 (ERTS-1), was launched on July 22, 1972. In 1975, NASA renamed the "ERTS" Program the "Landsat" Program and the name ERTS-1 was changed to Landsat-1. All following satellites carried the appellation of Landsat. As of 2002, there are seven Landsat satellites launched. The latest, Landsat-7 was launched on July 15, 1999.

Landsat-7 carries the Enhanced Thematic Mapper Plus (ETM+) sensor. The primary features of Landsat-7 include a panchromatic band with 49 ft (15 m) spatial resolution and a thermal infrared channel (Band 6) with 197 ft (60 m) spatial resolution. Like its predecessors the Landsat-4 and -5, Landsat-7 ETM+ includes the spectral bands 1,2,3,4,5,6 and 7. The spatial resolution remains at 98 ft (30 m), except for band 6 in which the resolution is increased from 394 ft (120 m) to 197 ft (60 m). Landsat-7 orbits Earth at an altitude of 438 mi (705 km). It has a repeat cycle of 16 days, meaning it returns to the same location every 16 days.

Radarsat is the series of space-borne SAR systems developed by Canada. Radarsat-1, launched on November 4, 1995 by NASA, carries a C-band 2.2 in (5.6 cm wavelength) antenna that looks to the right side of the platform. The antenna transmits at 5.3 GHz with an HH polarization (Horizontally transmitted, Horizontally received). It can be steered from 10 to 59 degrees. The swath width can be varied to cover an area from 31 mi (50 km) in fine mode to 311 mi (500 km) in ScanSAR Wide mode. Radarsat-1 orbits Earth at an altitude of 496 mi (798 km) and has a repeat cycle of 24 days.

Several space-borne remote sensing systems planned for launch in the near future include the Radarsat-2 and the Advanced Land Observing Satellite (ALOS) in 2003, and the Landsat-8 in 2005.

See also Archeological mapping; Earth, interior structure; Mapping techniques; Petroleum, history of exploration; RADAR and SONAR; Seismograph

REVOLUTION AND ROTATION

Although often confused, there is a distinct and important difference in the concepts of revolution and rotation. Earth rotates on its axis as it revolves around the **Sun**.

Earth rotates about its axis at approximately 15 angular degrees per hour. Rotation dictates the length of the diurnal cycle (i.e, the day/night cycle), creates "time zones" with differing local noons, and also causes the apparent movement of the **Moon**, stars, and planets across the "celestial sphere". The rotation of Earth is eastward (from west to east) making the apparent rotation of the celestial sphere from east to west.

The rates of rotation and revolution are functions of a planet's mass and orbital position. For example, the mass of Jupiter is approximately 317.5 times Earth's mass and the rotation time (the time for Jupiter to revolve once about its axis) is approximately nine hours.

Earth takes approximately 365.25 days to complete one revolution around the Sun in a slightly elliptical orbit with the Sun at one focal point of the ellipse. Ranging between the extremes of perihelion (closest approach) in January and aphelion (most distant orbital position) in July, Earth's orbital distance from the Sun ranges from approximately 91.5 to approximately 94 million miles (147–151 million km), respectively. Although these distances seem counterintuitive to residents of the Northern Hemisphere who experience summer in July and winter in January—the **seasons** are not nearly as greatly affected by distance as they are by changes in solar illumination caused by the fact that Earth's **polar axis** is inclined 23.5 degrees from the perpendicular to the ecliptic (the plane of the **solar system** through or near which most of the planet's orbits travel) and because the Earth exhibits parallelism (currently toward Polaris, the North Star) as it revolves about the Sun.

At the extreme of the solar system, Pluto, usually the most distant planet (i.e., at certain times Neptune's orbit actually extends farther than Pluto's orbit) takes approximately 247 Earth years (the time it takes the Earth to revolve about the Sun) to complete one orbital revolution about the Sun.

Rotation, revolution, polar tilt, parallelism, and Earth's oblate spheroid shape combine to produce an unequal distribution of **solar energy**, the changing of seasons, the changing lengths of day and night, and influence the circulation of the atmosphere and **oceans**.

In addition to Earth's rotation about the Sun, the solar system is both moving with the Milky Way galaxy and revolving around the galactic core.

See also Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars

RHYOLITE

Rhyolite is an **aphanitic** volcanic **rock** with the equivalent mineralogical composition of **granite**. Rhyolite contains less than 5% phenocrysts, or mineral grains visible without magnification. The rest of the more than 95% of the rock consists of a ground mass too fine to discern without magnification. This texture is the result of the rapid cooling of extruded **lava**, which does not allow sufficient time for larger **crystals** to grow.

The mineralogical composition of rhyolite is defined as containing mostly **quartz** and **feldspar** with a total silica content of more than 68%. Quartz in rhyolite may be as low as 10% but is usually present in amounts of 25% to 30%. Feldspars often comprise 50% to 70% of rhyolite, with potassium feldspar present in at least twice the amount of **plagioclase** feldspar. Ferromagnesian, or dark, **minerals** are rare as phenocrysts, being mostly biotite when present. Trace accessory minerals may also include muscovite, pyroxenes, amphiboles, and oxides.

Rhyolite often appears very uniform in texture, although lava flow structures may be evident. They range in color from white to gray to pink. Due to the fine grained nature, the differentiation of rhyolite from aphanitic rocks of differing composition is not always conclusive based on color alone, but any light colored volcanic aphanitic rock is likely to be a rhyolite.

The high silica content of rhyolite creates a high viscosity lava, or one that is strongly resistance to flow. The viscous lava tends to build up volcanic gases instead of allowing them to escape. Eruptions of rhyolite can be highly explosive due to the spontaneous release of large amounts of trapped gases. This accounts for some of the very quickly cooled textural variations of rhyolite. For example, **obsidian** is a pure volcanic **glass** of rhyolitic composition and **pumice** is rhyolite glass that has cooled in the form of gas bubbles.

See also Extrusive cooling

RICHARDSON, LEWIS FRY (1881-1953)

English physicist and meteorologist

Lewis Fry Richardson was an English physicist with a penchant for trying to solve a wide range of scientific problems using mathematics. During his career as a scientist and educator, Richardson explored mathematical solutions to predict **weather**, to explain the flow of **water** through peat, and to identify the origins of war.

Richardson was the youngest of seven children born to David Richardson, a tanner, and his wife, Catherine Fry, who came from a family of corn merchants. Richardson was born on October 11, 1881, in Newcastle upon Tyne. After completing his high school education in 1898, Richardson studied science at Durham College in Newcastle for two years before entering King's College at Cambridge, where he ultimately earned a doctorate in **physics** and then later returned to study and receive a degree in psychology. After graduating from King's College, Richardson held a number of positions in the years leading up to World War I. These included working as a scientist for a tungsten lamp factory, the National Peat Industries, Ltd., and serving four years as superintendent of the Eskdalemuir Observatory operated by the National Meteorological Office.

Richardson, who was born into a Quaker family, served with the French army as a member of the Friends' Ambulance Unit during the war from 1916 to 1919. Following the end of hostilities, Richardson returned to England, where he combined his scientific inquiry with teaching. In 1920, he accepted a position as director of the physics department at Westminster Training College. This was followed by an appointment as principal of Paisley Technical College in 1929, a post that he held until his retirement in 1940. Retirement allowed Richardson to continue his primary love, research.

Richardson began his research looking at practical problems, such as examining the flow of water through peat while he worked for the National Peat Industries, Ltd. Using differential equations, Richardson came up with ways to determine water flow that were far more accurate than other methods. His work eventually led to attempts at developing a system of weather prediction based on newly understood knowledge of the upper atmosphere and the roles played by radiation and eddies, or atmospheric currents which move contrary to main air flow. Richardson's work led to the publication of his book, *Weather Prediction by Numerical Process*, in 1922.

Richardson's experiences in France during the First World War also inspired him to probe the causes of human conflict using mathematics, and he published a paper in 1919 on the mathematical psychology of war. Eventually, he enlarged upon this early work in the book *Arms and Insecurity* and went on to complete a mathematical study of the world's wars. This work, which resulted in *Statistics of Deadly Quarrels*, examined the causes and magnitude of these conflicts. In his research, Richardson tried to define the relations between countries in terms of mathematical equations.

Richardson's pioneering use of mathematics resulted in him being elected a fellow in the Royal Society in 1926. Richardson died on September 30, 1953.

See also Atmospheric composition and structure; Weather forecasting methods; Weather forecasting

RICHTER, CHARLES F. (1900-1985)

American seismologist

Charles F. Richter is remembered every time an **earthquake** happens. With German-born seismologist Beno Gutenberg, Richter developed the scale that bears his name and measures the magnitude of earthquakes. Richter was a pioneer in seismological research at a time when data on the size and location of earthquakes were scarce. He authored two textbooks that are still used as references in the field and are regarded by many scientists as his greatest contribution, exceeding the more popular **Richter scale**. Devoted to his work all his life, Richter at one time had a **seismograph** installed in his living room, and he welcomed queries about earthquakes at all hours.

Charles Francis Richter was born on a farm near Hamilton, Ohio, north of Cincinnati. His parents were divorced when he was very young. He grew up with his maternal grandfather, who moved the family to Los Angeles in 1909. Richter went to a preparatory school associated with the University of Southern California, where he spent his freshman year in college. He then transferred to Stanford University, where he earned an A.B. degree in **physics** in 1920.

Richter received his Ph.D. in theoretical physics from the California Institute of Technology (Cal Tech) in 1928. That same year he married Lillian Brand of Los Angeles, a creative writing teacher. Robert A. Millikan, a Nobel Prize-winning physicist and president of Cal Tech, had already offered Richter a job at the newly established Seismological Laboratory in Pasadena, then managed by the Carnegie Institution of Washington. Thus Richter started applying his physics background to the study of the earth.

As a young research assistant, Richter made his name early when he began a decades-long collaboration with Beno Gutenberg, who was then the director of the laboratory. In the early 1930s, the pair was one of several groups of scientists around the world who were trying to establish a standard way to measure and compare earthquakes. The seismological laboratory at Cal Tech was planning to issue regular reports on southern California earthquakes, so the Gutenberg-Richter study was especially important. They needed to be able to catalog several hundred quakes a year with an objective and reliable scale.

At the time, the only way to rate shocks was a scale developed in 1902 by the Italian priest and geologist Giuseppe Mercalli. The Mercalli scale classified earthquakes from 1 to 12, depending on how buildings and people responded to the tremor. A shock that set chandeliers swinging might rate as a 1 or 2 on this scale, while one that destroyed huge buildings and created panic in a crowded city might count as a 10. The obvious problem with the Mercalli scale was that it relied on subjective measures of how well a building had been constructed and how used to these sorts of crises the population was. The Mercalli scale also made it difficult to rate earthquakes that happened in remote, sparsely populated areas.

The scale developed by Richter and Gutenberg, which became known by Richter's name only, was instead an absolute measure of an earthquake's intensity. Richter used a seismograph—an instrument generally consisting of a constantly unwinding roll of paper, anchored to a fixed place, and a pendulum or magnet suspended with a marking device above the roll—to record actual earth motion during an earthquake. The scale takes into account the instrument's distance from the epicenter, or the point on the ground that is directly above the earthquake's origin. Richter chose to use the term "magnitude" to describe an earthquake's strength because of his early interest in **astronomy**; stargazers use the word to describe the brightness of stars. Gutenberg suggested that the scale be logarithmic, so that a quake of magnitude 7 would be ten times stronger than a 6, a hundred times stronger than a 5, and a thousand times stronger than a 4. (The 1989 Loma Prieta earthquake that shook San Francisco was magnitude 7.1.)


Charles Richter. ***AP/Wide World. Reproduced by permission.***

The Richter scale was published in 1935, and immediately became the standard measure of earthquake intensity. Richter did not seem concerned that Gutenberg's name was not included at first; but in later years, after Gutenberg was already dead, Richter began to insist that his colleague be recognized for expanding the scale to apply to earthquakes all over the globe, not just in southern California. Since 1935, several other magnitude scales have been developed. Depending on what data is available, different ones are used, but all are popularly known by Richter's name.

For several decades, Richter and Gutenberg worked together to monitor seismic activity around the world. In the late 1930s they applied their scale to deep earthquakes, ones that originate more than 185 miles below the ground, which rank particularly high on the Richter scale—8 or greater. In 1941, they published a textbook, *Seismicity of the Earth*, which in its revised edition became a standard reference book in the field. They worked on locating the epicenters of all the major earthquakes and classifying them into geographical groups. All his life, however, Richter warned that seismological records only reflect what people have measured in populated areas and are not a true representative sample of what shocks have actually occurred. He long remained skeptical of some scientists' claims that they could predict earthquakes.

Richter remained at Cal Tech for his entire career, except for a visit to the University of Tokyo from 1959 to 1960 as a Fulbright scholar. He became involved in promoting good earthquake building codes, while at the same time discouraging the overestimation of the dangers of an earthquake in a populated **area** like Los Angeles. He pointed out that statistics reveal freeway driving to be much more dangerous than living in an earthquake zone. He often lectured on how loss of life and property damage were largely avoidable during an earthquake, with proper training and building codes—he opposed building anything higher than thirty stories, for example. In the early 1960s, the city of Los Angeles listened to Richter and began to remove extraneous, but potentially dangerous, ornaments and cornices from its buildings. Los Angeles suffered a major quake in February of 1971, and city officials credited Richter with saving many lives. Richter was also instrumental in establishing the Southern California Seismic Array, a network of instruments that has helped scientists track the origin and intensity of earthquakes, as well as map their frequency much more accurately. His diligent study resulted in what has been called one of the most accurate and complete catalogs of earthquake activity, the Cal Tech catalog of California earthquakes.

Later in his career, Richter would recall several major earthquakes. The 1933 Long Beach earthquake was one, which he felt while working late at Cal Tech one night. That quake caused the death of 120 people in the then sparsely populated southern California town; it cost the Depression-era equivalent of $150 million in damages. Nobel Prize-winning physicist **Albert Einstein** was in town for a seminar when the earthquake struck, according to a March 8, 1981 story in the *San Francisco Chronicle*. Einstein and a colleague of Richter's were crossing the campus at the time of the quake, so engrossed in discussion that they were oblivious to the swaying trees. Richter also remembered the three great quakes that struck in 1906, when he was a six-year-old on the Ohio farm. That year, San Francisco suffered an 8.3 quake, Colombia and Ecuador had an 8.9, and Chile had an 8.6.

In 1958, Richter published his text *Elementary Seismology*, which was derived from the lectures he faithfully taught to Cal Tech undergraduates as well as decades of earthquake study. Many scientists consider this textbook to be Richter's greatest contribution, since he never published many scientific papers in professional journals. *Elementary Seismology* contained descriptions of major historical earthquakes, tables and charts, and subjects ranging from the nature of earthquake motion to earthquake insurance and building construction. Richter's colleagues maintained that he put everything he knew into it. The book was used in many countries.

In the 1960s, Richter had a seismograph installed in his living room so that he could monitor quakes at any time. He draped the seismographic records—long rolls of paper covered with squiggly lines—over the backs of the living room chairs. (His wife, Richter maintained, considered the seismograph a conversation piece.) He would answer press queries at any hour of the night and never seemed tired of talking about his work. Sometimes he grew obsessive about speaking to the press; when a tremor happened during Cal Tech working hours, Richter made sure he would be the one answering calls—he put the lab's phone in his lap.

Richter devoted his entire life to **seismology**. He even learned Russian, Italian, French, Spanish, and German, as well as a little Japanese, in order to read scientific papers in their original languages. His dedication to his work was complete; in fact, he became enraged at any slight on it. For instance, at his retirement party from Cal Tech in 1970, some laboratory researchers sang a clever parody about the Richter scale. Richter was furious at the implication that his work could be considered a joke. During his lifetime he enjoyed a good deal of public and professional recognition, including membership in the American Academy of Arts and Sciences and a stint as president of the Seismological Society of America, but he was never elected to the National Academy of Sciences. After his retirement, Richter helped start a seismic consulting firm that evaluated buildings for the government, for public utilities such as the Los Angeles Department of **Water** and Power, and for private businesses.

Richter enjoyed listening to classical music, reading science fiction, and watching the television series *Star Trek*. One of his great pleasures, ever since he grew up walking in the southern California mountains, was taking long solitary hikes. Richter died in Pasadena at the age of 85.

See also Faults and fractures; Folds

RICHTER SCALE

The earliest **earthquake** measurements were simple descriptions called intensity ratings. These results were unreliable depending on the distance between the quake's source (epicenter), and the people evaluating the event.

A more systematic approach was developed by an Italian seismologist, Guiseppe Mercalli in 1902. He gauged earthquake intensity by measuring the damage done to buildings. The United States Coast and Geodetic Survey adapted his method, which they called the modified Mercalli Scale, dividing the measurements into 12 categories: level II was "felt by persons at rest," but at level VII it was "difficult to stand." Level X caused most buildings to collapse, and level XII, the most intense, combined ground fissures with tsunamis (tidal waves) and almost total destruction. Despite the specific detail of descriptions, this method, like the intensity ratings, was influenced by the measurement's distance from the earthquake's epicenter. Seismologists needed a way to determine the size, or magnitude, of an earthquake. They needed a quantitative, numerical measurement that would compare the strength of earthquakes in a meaningful way, not merely catalog damage or record perceptions as Mercalli's qualitative method did. This critical factor was finally determined in 1935 by American seismologist **Charles F. Richter**, a professor of **seismology** at the California Institute of Technology. His system of measurement, called the Richter scale, was based on his studies of earthquakes in southern California. It has become the most widely used assessment of earthquake severity in the world.

Richter measured ground movement with a **seismograph**, compared the reading to others taken at various distances from the epicenter, then calculated an average magnitude from all reports. The results are plotted on a logarithmic scale, in whole numbers and tenths, from 1 to 9. Each whole number increase means that the magnitude of the quake is ten times greater than the previous whole number. Thus, an earthquake with a magnitude of 6.5 has ten times the force of one with a magnitude of 5.5; an earthquake of 7.5 has 100 times the intensity of the 5.5 earthquake. An 8.5 measurement is 1,000 times stronger, and so on.

The amount of energy an earthquake releases is calculated in a different manner. Instead of tenfold jumps with each increase in magnitude, energy released is measured in roughly thirtyfold increments. Thus, an earthquake with a value of 7 releases 30 times the amount of energy as an earthquake measured at 6, while an earthquake of 8 would have 900 times the energy as one valued at 6.

Today the modified Mercalli scale is often used in combination with the Richter scale because both methods are helpful in gauging the total impact of an earthquake.

See also Seismology

RIDE, SALLY (1951-)

American astronaut

Sally Ride is best known as the first American woman sent into outer **space**. She also served the National Aeronautics and Space Administration (NASA) in an advisory capacity, and was the only astronaut chosen for President Ronald Reagan's Rogers Commission investigating the mid-launch explosion of the **space shuttle** *Challenger* in January, 1986, writing official recommendation reports and creating NASA's Office of Exploration. Both scientist and professor, she has served as a fellow at the Stanford University Center for International Security and Arms Control, a member of the board of directors at Apple Computer Inc., and a space institute director and **physics** professor at the University of California at San Diego. Ride has chosen to write primarily for children about space travel and exploration. Her commitment to educating the young earned her the Jefferson Award for Public Service from the American Institute for Public Service in 1984, in addition to her National Spaceflight Medals recognizing her two groundbreaking shuttle missions in 1983 and 1984.

Sally Kristen Ride is the older daughter of Dale Burdell and Carol Joyce (Anderson) Ride of Encino, California, and was born May 26, 1951. As author Karen O'Connor describes tomboy Ride in her young reader's book, *Sally Ride and the New Astronauts,* Sally would race her dad for the sports section of the newspaper when she was only five years old. An active, adventurous, yet also scholarly family, the Rides traveled throughout **Europe** for a year when Sally was nine and her sister Karen was seven after Dale took a sabbatical from his political science professorship at Santa Monica Community College. While sister Karen was inspired to become a minister, in the spirit of her parents who were elders in their Presbyterian church, Sally Ride's own developing taste for exploration would eventually lead her to apply to the space program almost on a whim. "I don't know why I wanted to do it," she confessed to *Newsweek* prior to embarking on her first spaceflight.

Astronaut Sally Ride suspended in a shuttle sleeping bag. ***U.S. National Aeronautics and Space Administration (NASA).***

From her earliest years in school, Ride was so proficient and efficient at once, she proved to be an outright annoyance to some of her teachers. Though she was a straight-A student she was easily bored, and her intellect only came to the fore in high school when she was introduced to the world of science by her physiology teacher. The impact of this mentor, Dr. Elizabeth Mommaerts, was so profound that Ride would later dedicate her first book primarily to her, as well as the fallen crew of the *Challenger*. While she was adept at all forms of sport, playing tennis was Ride's most outstanding talent, which she had developed since the age of ten. Under the tutelage of a four-time U.S. Open champion, Ride eventually ranked eighteenth nationally on the junior circuit. Her ability won her a partial scholarship to Westlake School for Girls, a prep school in Los Angeles. After graduating from there in 1968, Ride preferred to work on her game full time instead of the physics program at Swarthmore College, Pennsylvania, where she had originally enrolled. It was only after Ride had fully tested her dedication to the game that she decided against a professional career, even though tennis pro Billie Jean King had once told her it was within her grasp. Back in California as an undergraduate student at Stanford University, Ride followed her burgeoning love for Shakespeare to a double major, receiving B.S. and B.A. degrees in tandem by 1973. She narrowed her focus to physics for her masters, also from Stanford, awarded in 1975. Work toward her dissertation continued at Stanford; she submitted “The Interaction of X Rays with the Interstellar Medium” in 1978.

Ride was just finishing her Ph.D. candidacy in physics, **astronomy**, and astrophysics at Stanford working as a research assistant when she got the call from NASA. She became one of 35 chosen from an original field of applicants numbering 8,000 for the spaceflight training of 1978. “Why I was selected remains a complete mystery,” she later admitted to John Grossmann in a 1985 interview in *Health*. “None of us has ever been told.” Even after three years of studying x-ray astrophysics, Ride had to go back to the classroom to gain skills to be part of a team of astronauts. The program included basic science and math, **meteorology**, guidance, navigation, and computers as well as flight training on a T-38 jet trainer and other operational simulations. Ride was selected as part of the ground-support crew for the second (November, 1981) and third (March, 1982) shuttle flights, her duties including the role of “capcom,” or capsule communicator, relaying commands from the ground to the shuttle crew. These experiences prepared her to be an astronaut.

Ride would subsequently become, at 31, the youngest person sent into orbit as well as the first American woman in space, the first American woman to make two spaceflights, and, coincidentally, the first astronaut to marry another astronaut in active duty. She and Steven Alan Hawley were married in 1982. Hawley, a Ph.D. from the University of California, had joined NASA with a background in astronomy and astrophysics. When asked during a hearing by Congressman Larry Winn, Jr. of the House Committee on Science and Technology how she would feel when Hawley was in space while she remained earthbound, Ride replied, “I am going to be a very interested observer.” Eventually, the couple divorced.

Ride points to her fellow female astronauts Anna Fisher, Shannon Lucid, Judith Resnik, Margaret Seddon, and Kathryn Sullivan with pride. Since these women were chosen for training, Ride’s own experience could not be dismissed as tokenism, which had been the unfortunate fate of the first woman in orbit, the Soviet Union’s **Valentina Tereshkova**, a textile worker. Ride expressed her concern to *Newsweek* reporter Pamela Abramson in the week before her initial shuttle trip: “It’s important to me that people don’t think I was picked for the flight because I am a woman and it’s time for NASA to send one.’’

From June 18 to June 24, 1983, flight STS-7 of the space shuttle *Challenger* launched from Kennedy Space Center in Florida, orbited the earth for six days, returned to Earth, and landed at Edwards Air Force Base in California. Among the shuttle team’s missions were the deployment of international satellites and numerous research experiments supplied by a range of groups, from a naval research lab to various high school students. With Ride operating the shuttle’s robot arm in cooperation with Colonel John M. Fabian of the U.S. Air Force, the first **satellite** deployment and retrieval using such an arm was successfully performed in space during the flight.

Ride was also chosen for *Challenger* flight STS-41G, which transpired between October 5 and October 13, 1984. This time the robot arm was put to some unusual applications, including “ice-busting” on the shuttle’s exterior and readjusting a radar antenna. According to Henry S. F. Cooper, Jr., in his book *Before Lift-off,* fellow team member Ted Browder felt that because Ride was so resourceful and willing to take the initiative, less experienced astronauts on the flight might come to depend upon her rather than develop their own skills, but this mission also met with great success. Objectives during this longer period in orbit covered scientific observations of the earth, demonstrations of potential satellite refueling techniques, and deployment of a satellite. As STS-7 had been, STS-41G was led by Captain Robert L. Crippen of the U.S. Navy to a smooth landing, this time in Florida.

As leader of a task force on the future of the space program, Ride wrote *Leadership and America’s Future in Space.* According to *Aviation Week and Space Technology,* this status report initiated a proposal to redefine NASA goals as a means to prevent the “space race” mentality that might pressure management and personnel into taking untoward risks. “A single goal is not a panacea,” the work stated in its preface. “The problems facing the space program must be met head-on, not oversimplified.” The overall thrust of NASA’s agenda, Ride suggested, should take environmental and international research goals into consideration. A pledge to inform the public and capture the interest of youngsters should be taken as a given. Ride cited a 1986 work decrying the lack of math and science proficiency among American high school graduates, a mere 6% of whom are fluent in these fields, compared to up to 90% in other nations.

While with NASA, Ride traveled with fellow corps members to speak to high school and college students on a monthly basis. Speaking at Smith College in 1985, she announced that encouraging women to enter math and science disciplines was her “personal crusade.” Ride noted in *Publishers Weekly* the next year that her ambition to write children’s books had been met with some dismay by publishing houses more in the mood to read an autobiography targeted for an adult audience. Her youth-oriented books were both written with childhood friends. Susan Okie, coauthor of *To Space and Back*, eventually became a journalist with the *Washington Post. Voyager* coauthor Tam O’Shaughnessy, once a fellow competition tennis player, grew up to develop workshops on scientific teaching skills.

Ride left NASA in 1987 for Stanford’s Center for International Security and Arms Control, and two years later she became director of the California Space Institute and physics professor at the University of California at San Diego. She has flown Grumman Tiger aircraft in her spare time since getting her pilot’s license. The former astronaut keeps in shape when not teaching or fulfilling the duties of her various professional posts by running and engaging in other sports, although she once told *Health* magazine she often winds up eating junk food. Ride admitted not liking to run but added, “I like being in shape.”

See also Space physiology; Spacecraft, manned

RIFTING AND RIFT VALLEYS

Rifting is the process in which continental **crust** is extended and thinned, forming extensional sedimentary basins and/or **mafic** dyke-swarms. Rifts commence as intracratonic, downthrown blocks dominated by normal or oblique-extensional (transtensional) faults (e.g., the Rhine Graben in Germany and the East African Rift). Rift flanks may be uplifted. Continued rifting results in the break-up of continental plates and creation of oceanic crust (typically 20 to 60 million years after the onset of rifting, but ranging from 7 to 280 million years). Outpouring of flood basalts (also called traps, e.g., the Deccan Traps in western India) can occur over large areas prior to break-up. Marine **sedimentary rocks** are deposited over the rift sequence during the ensuing phase of post-rift, thermal subsidence.

Rifts commonly develop above upwelling convection cells in the **asthenosphere**, such as over a mantle plume. Extensional stresses are induced or enhanced by shear-traction on the base of the **lithosphere** by outwards asthenospheric flow from zones of upwelling. Continents may be split along rifts linking two or more **mantle plumes** (e.g., **South America** and **Africa** were separated along rifts linking the St. Helena, Tristan and Bouvet plumes). Rifting may also represent the far-field reactivation of pre-existing crustal weaknesses, such as old orogenic (mobile) belts, during collision at a distant convergent plate margin. For example, Permo-Triassic ‘Gondwanan’ rifts in southern Africa, India, and **Australia** represent the orthogonal or oblique extensional reactivation of Proterozoic orogenic belts on the margins of Archaean cratons during collision on the Paleopacific margin of Gondwanaland. Rifts develop in back-arc settings where extensional stresses can be induced by decreasing rates of plate convergence and/or rollback of a **subduction zone**. Small oceanic basins, such as the Sea of Japan, may form by back-arc rifting. Small rifts may also form by the stepping of transcurrent faults, such as the Salton Sea **area** of the San Andreas fault system in California.

An understanding of rift architecture and structural styles is important as rifts contain major hydrocarbon provinces and mineral deposits. The two main styles of rifting are pure-shear and simple-shear. Many rifts, however, exhibit different elements of these two end-member styles. In pure-shear rifting, steep to moderately dipping normal faults form symmetrically either side of the rift axis. Rift valleys (such as along the East African rift) are developed in the early stages of rifting. Rift valleys are elongate, wide, and typically flat-bottomed topographic depressions along down-thrown blocks. As rift valleys are bounded by normal faults, their sides tend to be steep. Continued crustal extension results in further subsidence and formation of a sedimentary basin along the rift axis. The asthenosphere is bowed upward as an isostatic response to lithospheric thinning. Mafic dykes may be intruded along fractures in the overlying crust. The area of thinnest crust corresponds to the shallowest asthensophere.

Other, highly asymmetrical rifts display a different pattern of structures. In early simple-shear rift models, a throughgoing shear zone was proposed to extend from the upper crust to the upper mantle. Brittle deformation along the upper part of the extensional detachment was thought to progressively change to ductile shearing over a broader zone at greater depth. It is now thought more likely that a zone of ductile flow in the lower to middle crust separates and decouples displacement along a shallowly dipping extensional detachment in the upper to middle crust from a normal shear zone cutting lithospheric mantle (possibly reactivating a former suture) or bowed up lithospheric mantle. In simple shear rifts, areas of greatest crustal thinning may be offset from areas of greatest asthenospheric uplift. Greatest heat flow and hence volcanic activity and dyke intrusion may be offset from a zone of highly extended crust. This zone comprises highly rotated blocks between imbricate, curved (listric) normal faults. Extensional detachments may be folded by regional antiforms during asthenospheric uplift. The opposite margins of two continents rifted apart may therefore be quite dissimilar. The lower plate margin may show a broad zone of shallowly dipping listric normal faults draped by shallowly dipping sedimentary strata deposited during the post-rift, thermal subsidence phase. Dykes and volcanic rocks may be absent to sparse. In contrast, the opposite, upper plate margin may comprise a narrow zone of steeply dipping faults and contain volcanic rocks and dykes.

See also Continental drift theory; Earth, interior structure; Faults and fractures; Orogeny; Plate tectonics

RIP CURRENT

A rip current is a narrow, river-like channel of **water** moving away from the surf (breaking) zone and back toward sea. Rip currents can travel up to 3 mph (4.8 kph) and stretch 100 ft (30.5 m) wide. Some cease just past the breaking surf; others extend a thousand feet offshore. In some regions, the rip current, or rip tide, is a permanent feature of the sea. In other areas, one can appear suddenly or intensify after a storm or a breach in an offshore sandbar.

Rip currents are fed by long shore currents, or feeders, which flow parallel to the beach inside the **surf zone**. In addition to the feeder, each current consists of a neck (main channel) and a head. The neck is the point where feeder currents converge and move back out to sea through a weak spot in the breakers. The head is the widest part of the rip current. Rip currents are typically found near jetties of irregular beaches and along straight, uninterrupted beaches. Although often mistakenly called one, a rip current is not an undertow.

Telltale signs of a rip current include murkier or darker waters, changes in wave formation (large, choppier waves inside the current, calmer ones up front), and foam moving seaward.

Rip currents are dangerous to swimmers, who may suddenly be pulled far out to sea or underwater. ***Courtesy of Kelly A. Quin.***

The intense currents can pull even the most experienced swimmer into dangerously deep ocean water. Attempting to swim to safety against the current can result in exhaustion, panic, and sometimes drowning. An estimated 80% of United States lifeguard rescues are due to rip currents. Experts advise swimming parallel to shore until you surpass the current, then head toward land. Inexperienced swimmers should tread water and call for help.

See also Ocean circulation and currents; Surf zone

RITTER, CARL (1779-1859)

German geographer

Along with his countryman and mentor **Alexander von Humboldt** (1769–1859), Carl Ritter is recognized as one of the two founders of modern geography.

Ritter was born the son of a physician on August 7, 1779, in Quedlinburg, Germany. After his father's premature death in 1784, his mother enrolled him at the age of five in Schnepfenthal, the experimental school of Christian Gotthilf Salzmann (1744–1811), where he acquired an amazing breadth of basic education. Based on the humanistic pedagogical theories of Jean Jacques Rousseau (1712–1778), Salzmann's system emphasized empirical science, practical living, natural law, history, philosophy, theology, art, and modern languages, but not classical languages. His geography teacher was Johann Christoph Friedrich GutsMuths (1759–1839), who also taught history and French. Upon completing this curriculum, Ritter was hired as private tutor for the children of Bethmann Hollweg, a wealthy banker in Frankfurt. From 1798 to 1814, he worked for Hollweg, who financed his university education, first at Frankfurt, then at Göttingen from 1813 to 1819. During this time he also taught himself Latin and Greek.

Ritter's first geographical publication appeared in 1804. By 1816, he was a well-established scholar, with many articles and a two-volume textbook of European geography. He had traveled throughout **Europe**, but not beyond it. On the strength of his excellent reputation, he became professor of history at the University of Frankfurt in 1819 then in 1820 professor of geography at the University of Berlin, holding Germany's first endowed professorship of geography. He spent the rest of his career there, enjoying honors as a popular lecturer and prolific writer. Among his students at Berlin was the geologist **Arnold Henri Guyot** (1807–1884). While in Berlin, he also taught at a military academy and, in 1828, co-founded the Berlin Geographical Society. He died in Berlin on September 28, 1859.

A child of the Enlightenment, Ritter developed a strong affinity for the progressive ideas of Swiss educator Johann Heinrich Pestalozzi (1746–1827), German philosopher Johann Gottfried von Herder (1744–1803), and Humboldt. He integrated the studies of history and geography, perhaps sometimes to the disadvantage of traditional **physical geography**. He envisioned his life's work as a comprehensive geographical treatise of the entire world. With a long title but commonly known as simply *Erdkunde* (Geography), the first volume appeared in 1817. Eventually it ran to nineteen volumes, but when Ritter died it was still incomplete, covering only **Asia** and **Africa**. Immediately successful, it defined the discipline of geography as the study of the relation between humans and their various environments throughout the world. The human aspect of the study was Ritter's innovation, based on GutsMuths's principles. Geography was no longer "just maps."

See also Earth science

RIVERS

Rivers and streams are bodies of flowing surface **water** that transport sediment from continental highlands to **lakes**, alluvial fans, and ultimately the ocean. Streams are the main agent of **erosion** of the earth's continental **crust**, and they play a major role in shaping the landscape. Streams are also a focus of humans' interaction with our environment. Human agriculture, industry, and essential biology require fresh, accessible water. Ancient human civilizations first arose in the fertile val-

The Nile River as viewed from the space shuttle. The Nile is the longest river in the world. ***AP/Wide World. Reproduced by permission.***

leys of some of the world's greatest rivers: the Yangtze and Yellow Rivers in China, the Tigris and Euphrates Rivers in the Middle East, and the Nile in Egypt. The distribution of the earth's river systems has influenced human population patterns, commerce, and conquest since then, and the availability of uncontaminated surface water for irrigation, industrial and municipal uses remains a pressing geopolitical issue.

Streamflow is a gravity-driven process that acts to level continental **topography**. Stream erosion balances uplift at plate tectonic boundaries by mechanically and chemically eroding upland rocks, and transporting the resulting siliclastic sediments and dissolved ions and molecules toward the ocean. Current velocity determines a stream's capacity to transport a given volume of suspended and bedload sediment. Sediment transport is intermittent, and individual grains are deposited and re-entrained by turbulent streamflow many times before final deposition in deltas and alluvial fans.

Stream erosion and deposition act in dynamic equilibrium to maintain a concave longitudinal stream profile, called a graded profile, with steep headwaters to low-gradient downstream portions. The elevation where a stream enters another body of water, called base level, controls the downstream end of a stream profile, and the elevation of the headwaters determines the upstream end. Streams cannot erode below base level. Sea level is the ultimate base level for most river systems, and a sea-level change creates a string of compensatory adjustments throughout a stream system. Base level for an individual tributary, however, is controlled by the elevation of the next body of water it enters. If base level falls, or uplift occurs, current velocity increases, and the stream erodes downward. If base level rises, or subsidence occurs, a stream slows down and deposits sediment.

Streams flow in valleys that encompass an **area** between uplands. Some rivers carve their own valleys, and some flow in preexisting valleys created by other geologic processes like **rifting** or glacial erosion. The stream channel that contains flow during non-flood times runs through the stream valley flanked by its overspill areas called **floodplains**. Over time, a stream fills its valley with its own deposits; the **stratigraphy** of a river basin thus shows the depositional history of the stream. Most streams have a valley, a channel, and a floodplain, but their morphology varies between three end-member types—straight, meandering, and braided—depending on the stream gradient, the rate of sediment supply, and the sediment grain size.

Straight streams develop in regions where uplift and/or base level fall force rapid regrading by channel incision. Meandering streams develop at the low-gradient, downstream ends of stream profiles. Because they cannot erode below base level, streams near base level maintain their profile by moving horizontally across the stream valley, eroding and depositing sediment with little effect on the overall sediment flux. Meandering streams develop an organized pattern of fluvial **landforms** and deposits: coarse-grained point bars, gravel channel lags, sandy natural levees, abandoned meanders called oxbow lakes, and fine-grained flood deposits. Braided streams form in mountainous and glaciated areas where rapid currents, voluminous sediment supply, and coarse-grained sediment prevent a stream from forming an orderly pattern of channels and bars. Braided streams have many interlaced channels separated by longitudinal gravel bars that shift over time.

Stream systems are organized into **drainage basins** with small tributary streams that feed into larger trunk streams, and finally into a major river that lets out into the ocean. Drainage divides are topographic highs that separate drainage basins. Drainage basins and divides vary in scale from small hillside watersheds separated by ridges, to the two halves of the North American continent separated by the **continental divide** along the spine of the Rocky Mountains. The outcrop pattern of underlying geologic strata determines the geometry of a stream system. Tree-shaped, or dendritic, drainage patterns form when water flows randomly downhill without encountering geologic obstacles or conduits. Dendritic drainages are the most common and form when **bedrock** layers are horizontal. Trellis-shaped drainages develop in continental fold belts. Rectangular patterns are common in areas of fractured crystalline rocks, and streams flow down the sides of volcanoes in a radial pattern.

See also Alluvial systems; Drainage basins and drainage patterns; Canyon; Estuary; Hydrogeology; Sedimentation; Stream capacity and competence; Stream piracy; Stream valleys, channels, and floodplains

ROCHE MONTONEU • *see* GLACIAL LANDFORMS

ROCK

To the geologist, the term rock means a naturally occurring aggregate of **minerals** that may include some organic solids (e.g., **fossils**) and/or **glass**. Rocks are generally subdivided into three large classes: igneous, sedimentary, and metamorphic. These classes relate to common origin, or genesis. **Igneous rocks** form from cooling liquid rock or related volcanic eruptive processes. **Sedimentary rocks** form from compaction and cementation of sediments. Metamorphic rocks develop due to solid-state, chemical and physical changes in pre-existing rock because of elevated **temperature**, pressure, or chemically active fluids.

With igneous rocks, the aggregate of minerals comprising these rocks forms upon cooling and crystallization of liquid rock. As **crystals** form in the liquid rock, they become interconnected to one another like jigsaw puzzle pieces. After total crystallization of the liquid, a hard, dense igneous rock is the result. Also, some volcanic lavas, when extruded on the surface and cooled instantaneously, will form a natural glass. Glass is a mass of disordered atoms, which are frozen in place due to sudden cooling, and is not a crystalline material like a mineral. Glass composes part of many extrusive igneous rocks (e.g., **lava** flows) and pyroclastic igneous rocks. Alternatively, some igneous rocks are formed from volcanic processes, such as violent volcanic eruption. Violent eruptions eject molten, partially molten, and non-molten igneous rock, which then falls in the vicinity of the eruption. The fallen material may solidify into a hard mass, called pyroclastic igneous rock. The texture of igneous rocks (defined as the size of crystals in the rock) is strongly related to cooling rate of the original liquid. Rapid cooling of liquid rock promotes formation of small crystals, usually too small to see with the unaided eye. Rocks with this cooling history are called fine-textured igneous rocks. Slow cooling (which usually occurs deep underground) promotes formation of large crystals. Rocks with this cooling history are referred to as coarse-textured igneous rocks.

The mineral composition of igneous rocks falls roughly into four groups: **silicic**, intermediate, **mafic**, and ultramafic. These groups are distinguished by the amount of silica (SiO_4), **iron** (Fe), and magnesium (Mg) in the constituent minerals. Mineral composition of liquid rock is related to place of origin within the body of the earth. Generally speaking, liquids from greater depths within the earth contain more Fe and Mg and less SiO_4 than those from shallow depths.

In sedimentary rocks, the type of sediment that is compacted and cemented together determines the rock's main characteristics. Sedimentary rocks composed of sediment that has been broken into pieces (i.e., clastic sediment), such as gravel, **sand**, silt, and **clay**, are clastic sedimentary rocks (e.g., conglomerate, **sandstone**, siltstone, and shale, respectively). Sedimentary rocks composed of sediment that is chemically derived (i.e., chemical sediment), such as dissolved elements like calcium (Ca), sodium (Na), iron (Fe), and **silicon** (Si), are chemical sedimentary rocks. Examples of chemical sedimentary rocks are **limestone** (composed of calcium carbonate), rock salt (composed of sodium chloride), rock **gypsum** (composed of calcium sulfate), ironstones (composed of iron oxides), and **chert** (composed of hydrated silica). Biochemical sedimentary rocks are a special kind of chemical sedimentary rock wherein the constituent particles were formed by organisms (typically as organic hard parts, such as shells), which then became sedimentary particles. Examples of this special kind of sedimentary rock include chalk, fossiliferous limestone, and coquina. Sedimentary rocks are formed from sediment in two stages: compaction and cementation. Compaction occurs when sediments pile up to sufficient thickness that overlying mass squeezes out **water** and closes much open **space**. Cementation occurs when water flowing through the

Pebbles on lake shore. © *Paul A. Souders/Corbis. Reproduced by permission.*

compacted sediment deposits mineral crystals upon particles thus binding them together. The main cement minerals are calcite ($CaCO_3$), hematite (Fe_2O_3), and **quartz** (SiO_2).

With metamorphic rocks, the nature of the pre-existing rock (protolith) determines in large part the characteristics of the ultimate **metamorphic rock**. Regardless of protolith, however, almost all metamorphic rocks are harder and more dense than their protoliths. A protolith with flat or elongate mineral crystals (e.g., micas or amphiboles) will yield a metamorphic rock with preferentially aligned minerals (due to directed pressure). Such metamorphic rocks are called foliated metamorphic rocks (e.g., **slate** and **schist**). Non-foliated metamorphic rocks (e.g., **marble** and quartzite) come from protoliths that have mainly equidimensional mineral crystals (e.g., calcite and quartz, respectively). For example, a protolith shale will yield a foliated metamorphic rock, and a protolith limestone will yield marble, a non-foliated metamorphic rock. Metamorphic rocks possess distinctive grades or levels of metamorphic change from minimal to a maximum near total **melting**. Low-grade metamorphic rocks generally have fine-textured crystals and low-temperature indicator minerals like the mica chlorite. High-grade metamorphic rocks generally have coarse-textured crystals and very distinctive foliation, plus high-temperature indicator minerals like the silicate mineral staurolite.

Rock is a brittle natural solid found mainly in the outer reaches of Earth's **crust** and upper mantle. Material that would be brittle rock at such shallow depths becomes to one degree or another rather plastic within the body of the earth. The term "rock" is not generally applied to such non-brittle internal Earth materials. Therefore, rock is a concept related to the outer shell of the earth. The term rock may also be properly applied to brittle natural solids found on the surfaces of other planets and satellites in our **solar system**. Meteorites are rock. Naturally occurring **ice** (e.g., brittle water ice in a glacier, H_2O) is also a rock, although we do not normally think of ice this way.

Rock has been an important natural resource for people from early in human **evolution**. Rocks' properties are the key to their specific usefulness, now as in the past. Hard, dense rocks that could be chipped into implements and weapons were among the first useful possessions of people. Fine-textured and glassy rocks were particularly handy for these applications. Later on, rock as building stone and pavement material became very important, and this continues today in our modern world. All of Earth's natural mineral wealth, fossil energy resources, and most **groundwater** are contained within rocks of the earth's crust.

See also Lithification; Metamorphism

ROCK AGE • *see* DATING METHODS

ROCKETS • *see* SPACECRAFT, MANNED

ROCKFALL

Rockfall is a form of **mass movement** or **mass wasting** in which pieces of **rock** travel downward through some combination of falling, bouncing, and rolling after they are initially separated from the slope. The sizes of rockfall blocks can range from cubic centimeters to tens of thousand of cubic meters. Although some sliding may occur as the rock is becoming detached, sliding is a minor component of the process. Free fall typically occurs on slopes steeper than 76 degrees, bouncing on slopes between 45 and 76 degrees, and rolling on slopes below 45 degrees. Because slopes are commonly irregular, a rock may alternate between the three modes during its downslope movement. Talus slopes along the bases of cliffs are the products of uncounted rockfalls over thousands of years.

The size of rockfall blocks is controlled by **bedding** planes, joints, and fractures that form mechanical discontinuities and allow the blocks to become detached from the slope. Fracture lengths, and therefore rockfall volumes, tend to follow power law or fractal distributions, meaning that their numbers decrease exponentially as fracture length or rockfall volume increases. Field studies have also shown that **freezing and melting** of **ice** within cracks may control rockfall timing in some areas, although the falls generally seem to be more closely related to **melting** rather than ice wedging.

Extremely large rockfalls can constitute **catastrophic mass movements** because their weight and vertical fall distance (which combine to define the potential energy of the rock before it falls) produce potentially destructive kinetic energy. A large rockfall in Yosemite National Park during the summer of 1996, for example, involved two large rock slabs with a total volume of between 30,000 and 49,700 yd^3 (23,000 and 38,000 m^3) that became detached from a cliff face and became airborne 2,181 ft (665 m) above the valley floor. The estimated velocity of the slabs at impact was approximately 246–268 mph (396–431 kph) and the event was recorded on seismographs as far as 124 mi (200 km) away. The impact produced an air blast with estimated velocities as high as 246 mph, which snapped and uprooted trees, generated a dense cloud of dust that plunged the **area** into darkness, and killed a hiker. The catastrophic rock avalanches, such as those that destroyed the towns of Elm, Austria and Frank, Alberta probably also involved significant amounts of rockfall that evolved into rock avalanches as they moved downslope.

See also Landslide; Talus pile or Talus slope

RODINIA • *see* SUPERCONTINENTS

ROTATION • *see* REVOLUTION AND ROTATION

ROWLAND, F. SHERWOOD (1927-)

American atmospheric chemist

In 1974, F. Sherwood Rowland and his research associate, **Mario Molina**, first sounded the alarm about the harmful effects of chlorofluorocarbons, or CFCs, on the earth's ozone layer. CFCs, which have been used in air conditioners, refrigerators, and aerosol sprays, release chlorine atoms into the upper atmosphere when the sun's ultraviolet light hits them. The chlorine then breaks down atmospheric **ozone** molecules, destroying a shield that protects the earth from damaging **ultraviolet rays**. In the mid–1980s, a National Aeronautics and Space Administration (NASA) **satellite** actually confirmed the existence of a continent-sized hole in the ozone layer over **Antarctica**. By the early 1990s, National Oceanographic and Atmospheric Administration (NOAA) scientists warned that yet another ozone hole, this one over the Arctic, could imperil Canada, Russia, **Europe**, and, in the United States, New England. This news might have been gratifying affirmation for Rowland, a professor of **chemistry** at the University of California at Irvine, but rather than rest on his laurels he continued to steadfastly and soberly warn the world of the ozone danger. His efforts have won him worldwide renown and prestigious awards, including the Charles A. Dana Award for Pioneering Achievement in Health in 1987, the Peter Debye Award of the American Chemical Society in 1993, the Roger Revelle Medal from the American Geophysical Union for 1994, and the Japan Prize in Environmental Science and Technology, presented to Rowland by the Japanese emperor in 1989.

Frank Sherwood Rowland was born in Delaware, Ohio, the son of a math professor, Sidney A. Rowland, and his wife, Latin teacher Margaret Drake Rowland. In an interview with Joan Oleck, Rowland claimed that math always came easy for him. "I always liked solving puzzles and problems," he said. "I think the rule we had in our family that applied even to my own children was you had your choice in school as to what order you took biology, chemistry, and **physics**, but not whether."

Sidetracked by World War II, Rowland was still in boot camp when peace arrived. In 1948, he received his B.A. degree from Ohio Wesleyan University; after three years—the summers of which he spent playing semiprofessional baseball—he obtained his master's from the University of Chicago. His Ph.D. came a year later, in 1952. That same year he married Joan E. Lundberg; the couple would eventually have a son and daughter.

Also in 1952, Rowland obtained his first academic job, an instructorship in chemistry at Princeton University, where he would remain for four years. In 1956, Rowland moved his family west to the University of Kansas, where he was a professor for eight years, and then farther west still, to Irvine, California, where he took over as chemistry department chairman at the University of California in Irvine in 1964. He has stayed at Irvine ever since, enjoying stints as Daniel G. Aldrich, Jr., Professor of Chemistry from 1985 to 1989, and as Donald Bren Professor of Chemistry since 1989.

At Chicago, Rowland's mentor had been **Willard F. Libby**, winner of the Nobel Prize for his invention of carbon–14 dating, a way to determine the age of an object by measuring how much of a radioactive form of **carbon** it contains. The **radioactivity** research Rowland conducted with Libby led the young scientist eventually to **atmospheric chemistry**. Realizing, as he told Oleck, that "if you're going to be a professional scientist, one of the things you're going to do is stay out ahead of the pack," Rowland looked for new avenues to explore. In the 1970s, Rowland was inspired by his daughter's dedication to the then-fledgling environmental movement and by the tenor of the times: 1970 was the year of the first Earth Day. In 1971, the chemist helped allay fears about high levels of mercury in swordfish and tuna by showing that preserved museum fish from a hundred years earlier contained about the same amount of the element as modern fish.

Later events pushed him further in the direction of environmental concerns. At a meeting in Salzburg, Austria, Rowland met an Atomic Energy Commission (AEC) staffer who was trying to get chemists and meteorologists into closer partnerships. Sharing a train compartment with the AEC man to Vienna, Rowland was invited to another professional meeting. And it was there, in 1972, that he first began to think about chlorofluorocarbons in the atmosphere.

In those days, production of CFCs for household and industrial propellants was doubling every five years. A million tons of CFCs were being produced each year alone, but scientists were not particularly alarmed; it was believed they were inert in the atmosphere. Rowland, however, wanted to know more about their ultimate fate. Ozone, a form of **oxygen**, helps make up the **stratosphere**, the atmospheric layer located between eight and 30 miles above the earth. Ozone screens out dangerous ultraviolet rays, which have been linked to skin cancer, malfunctions in the immune system, and eye problems such as cataracts. Performing lab experiments with Molina, Rowland reported in 1974 that the same chemical stability that makes CFCs useful also allows them to drift up to the stratosphere intact. Once they rise thorough the ozone shield, Rowland and Molina warned, they pose a significant threat to ozone: each chlorine **atom** released when CFCs meet ultraviolet light can destroy up to one hundred thousand ozone molecules.

Sounding the alarm in the journal *Nature* in June of 1974 and in a subsequent presentation to the American Chemical Society that September, Rowland attracted attention: a federal task force found reason for serious concern; the National Academy of Sciences (NAS) confirmed the scientists' findings; and by 1978, the Environmental Protection Agency (EPA) had banned nearly all uses of CFC propellants. There were setbacks: In the 1980s President Ronald Reagan's EPA administrator, Anne Gorsuch, dismissed ozone depletion as a scare tactic. And Rowland himself discovered that the whole matter was more complex than originally thought, that another chemical reaction in the air was affecting calculations of ozone loss. The NAS's assessment of the problem was similarly vague, generalizing future global ozone losses as somewhere between 2%–20%.

Then came a startling revelation. In the mid–1980s a hole in the ozone shield over Antarctica the size of a continent was discovered; NASA satellite photos confirmed it in 1985. The fall in ozone levels in the **area** was drastic, as high as 67%. These events led to increased concern by the international community. In 1987 the United States and other CFC producers signed the Montreal Protocol, pledging to cut production by 50% by the end of the millennium. Later, in the United States, President George Bush announced a U.S. plan to speed up the timetable to 1995.

There were more accelerations to come: Du Pont, a major producer, announced plans to end its CFC production by late 1994, and the European Community set a 1996 deadline. And producers of automobile air-conditioning and seat cushions—two industries still using CFCs—began looking for alternatives. These goals only became more urgent in the face of the 1992 discovery of another potential ozone hole, this one over the Arctic. Scientists have attributed the extreme depletion of ozone over the poles to **weather** patterns and seasonal **sun** that promote an unusually rapid cycle of chlorine-ozone chain reactions.

In addition to the development of holes in the ozone layer, the atmosphere is further threatened because of the time delay before CFCs reach the stratosphere. Even after a complete ban on CFC production is achieved, CFCs would continue to rise through the atmosphere, and were predicted to reach peak concentrations in the late 1990s. Some remained skeptical of the dangers, however. In the early 1990s a kind of "ozone backlash" occurred, with a scientist as prominent as Nobel Prize-winning chemist Derek Barton joining those who called for a repeal of the CFC phase-out pact.

Meanwhile Rowland continued his examination of the atmosphere. Every three months, his assistants have fanned out around the Pacific Ocean to collect air samples from New Zealand to Alaska. The news from his research has been sobering, turning up airborne compounds that originated from the burning of rain **forests** in Brazil and the aerial pollution of oil fields in the Caucasus mountains. "The major atmospheric problems readily cross all national boundaries and therefore can affect everyone's security," Rowland said in his President's Lecture before the American Association for the Advancement of Science (AAAS) in 1993. "You can no longer depend upon the 12-mi (19.3-km) offshore limit when the problem is being carried by the winds." An instructive reminder of the international nature of such insecurity was given by the arrival only two weeks later in Irvine, California, of trace amounts of the radioactive fission products released by the 1986 Chernobyl nuclear reactor accident in the former Soviet Union.

Rowland has said in interviews that he's pleased with the progress he's helped set in motion. "One of the messages is that it is possible for mankind to influence his environment negatively," Rowland told Oleck. "On the other side there's the recognition on an international basis that we can act in unison. We have the [Montreal] agreement, people are following it, and it's not only that they have said they will do these things but they *are* doing them because the measurements in the atmosphere show it. People have worked together to solve the problem."

See also Atmospheric circulation; Atmospheric composition and structure; Atmospheric pollution; Ozone layer and hole dynamics

RUNCORN, S.K. (1922-1995)

English geophysicist

Geophysicist S.K. Runcorn made significant contributions to the understanding of several areas within his field, including Earth's **magnetism** and the theory of continental drift. During the 1950s, he helped establish the discipline of paleomagnetism—the study of the intensity and direction of residual magnetization found in ancient rocks. Later, his research encompassed lunar **magnetism**. Runcorn published prolifically, with the publication of more than 180 papers and editing over two dozen books.

Stanley Keith Runcorn was born on November 19, 1922 in Southport, England. He was the eldest of two children born to William Henry Runcorn, a businessman, and Lily Idina Roberts Runcorn. As Runcorn related to contributor Linda Wasmer Smith in a letter, "My interest in science as a child was certainly stimulated... by excellent maths and **physics** teaching in my grammar school." In 1941, Runcorn began studies at Gonville and Caius College of Cambridge University. He passed the tripos, or final honors examination, in mechanical sciences two years later. Runcorn earned a B.A. degree from Cambridge in 1944 and an M.A. in 1948, before transferring to Manchester University to obtain a Ph.D. in 1949. Later, he returned to Cambridge, where he received an Sc.D. degree in 1963.

Runcorn's early years at college coincided with World War II. From 1943 through 1946, he worked on radar research for the ministry of supply at Malvern. For three years afterward, he was a lecturer in physics at Manchester University. His department head there was **Patrick Maynard Stuart Blackett**, who won the 1948 Nobel Prize in physics. Under Blackett's leadership, Runcorn first began a long line of investigations into geomagnetism, which extended well past his move back to Cambridge as assistant director of geophysics research in 1950.

At the time, the idea was rapidly gaining currency in England that many rocks contain within them a fossilized record of the magnetic conditions under which they were formed. This is the basic assumption behind paleomagnetic research. Runcorn compared the results of tests done on rocks from Great Britain and the United States. His analysis seemed to support the hypothesis that over hundreds of millions of years the earth's magnetic poles had undergone large-scale movement, or polar wandering. However, the polar migration routes were different depending on whether the tested rocks came from **Europe** or **North America**. This suggested that the continents themselves had actually moved. Thus, Runcorn became a proponent of the theory called continental drift. Although this idea had first been put forth in 1912, it had not up to that point won widespread acceptance. It was not until the mid-1950s that Runcorn and his colleagues published convincing evidence for its existence.

Advocates of continental drift argued that the direction of magnetization within rocks from different continents would align if only the land masses were oriented differently. However, this suggestion was not immediately embraced by most scientists, partly because a physical mechanism to explain continental drift had yet to be found. By the early 1960s, though, Runcorn had proposed that, under very high **temperature** and pressure, rocks beneath Earth's cold, outer shell—the lithosphere—might gradually "creep," or flow. The resulting upward transfer of heat by convection currents could be the force that moved continents. This idea contributed to the modern theory of **plate tectonics**, which posits that the earth's shell is divided into a number of rigid plates floating on a viscous underlayer.

In 1956, Runcorn accepted a post as professor and head of the physics department at King's College, part of the University of Durham. Seven years later, King's College became the University of Newcastle upon Tyne, and Runcorn was appointed head of the school of physics there, a position he held until 1988. During this period, Runcorn was also a visiting scientist or professor at several institutions around the world, including the University of California, Los Angeles and Berkeley; Dominion Observatory, Ottawa; the California Institute of Technology; the University of Miami; the Lunar Science Institute, Houston; the University of Texas, Galveston; and the University of Queensland, **Australia**.

By the late 1960s, Runcorn's attention had turned toward the **Moon**. At the time, the Moon was generally presumed to be a dead body. As early as 1962, though, Runcorn had suggested that the Moon, too, might be subject to the forces of convection—an idea that was initially rejected by most scientists. However, examination of lunar samples brought back by the Apollo missions showed that some of them were magnetized, which implied that they had been exposed to magnetic fields while they were forming. Runcorn and his colleagues concluded that the Moon had probably once possessed its own strong **magnetic field**, generated within an **iron** core.

This magnetic field seemed to have pointed in different directions at different times in lunar history. When Runcorn and his co-workers calculated the strengths and directions of this ancient magnetism, they found evidence of polar wandering. Runcorn subsequently proposed that the wandering could have been caused by the same impacts that created large basins near the Moon's equator. According to this hypothesis, the force of the impacts could have shifted the Moon's entire surface, so that regions once near the poles might have been relocated closer to the equator. However, attempts to confirm this notion have so far proved inconclusive.

Runcorn's remarkable skill as a theorist was widely recognized. In 1989, he assumed an endowed chair in the natural sciences at the University of Alaska in Fairbanks, a position he held until his death. He also received honorary degrees from universities in Utrecht, Netherlands; Ghent, Belgium; Paris; and Bergen, Norway. Among the many prestigious awards he received are the Napier Shaw Prize of Britain's Royal Meteorological Society in 1959, the John Adams Fleming Medal of the American Geophysical Union in 1983, the Gold Medal of Britain's Royal Astronomical Society in 1984, and the Wegener Medal of the European Union of Geosciences in 1987.

In addition, Runcorn was elected a fellow or member of such respected associations as the British Royal Society, the American Physical Society, the European Geophysical Society, the Royal Netherlands Academy of Science, the Indian National Science Academy, the Royal Norwegian Academy of Science and Letters, the Pontifical Academy of Science, and Academia Europaea.

Runcorn, who never married, was an aficionado of sports and the arts. Among his favorite pastimes was rugby, which he enjoyed as a participant until he was past fifty and as a spectator thereafter. In a letter to Wasmer Smith, Runcorn described himself also as an avid fan of "squash rackets and swimming,... visiting art galleries, seeing opera and ballet, reading history and politics, hiking in the country, and seeing architecture in my travels." Runcorn died at the age of 73 during a lecture tour stop in San Diego, California, where he was robbed and murdered in his hotel room.

See also Continental drift theory; Magnetic field; Paleomagnetics

RUNOFF

Runoff is the component of the **hydrologic cycle** through which **water** is returned to the ocean by overland flow. The term runoff is considered synonymous with streamflow and comprises surface runoff resulting from **precipitation** and that portion of the streamflow that is contributed by **groundwater** flow entering the stream channel.

Surface runoff consists of that portion of the precipitation reaching the surface that neither infiltrates into the ground nor is retained on the surface. The quantity of surface runoff is controlled by a complex variety of factors. Included among these are precipitation intensity and duration, **permeability** of the ground surface, vegetation type and density, **area** of drainage basin, distribution of precipitation, stream-channel geometry, depth to **water table**, and topographic slope.

In the early stages of a storm, much of the precipitation may be intercepted by vegetation or captured in surface depressions. Water held in this manner often presents a large surface area and is likely to be evaporated. Any water reaching the surface at this stage is more likely to infiltrate before the upper layer of the ground becomes saturated. Thus, storms of light intensity or short duration may produce little or no surface runoff. As storm intensity or duration increases, interception becomes less effective, infiltration capacity of the **soil** decreases, and surface depressions fill. The result is increasing surface runoff leading to greater flow rates within local stream channels.

Variations in permeability within the soil may cause a portion of the water that infiltrates into the soil to migrate laterally as interflow. Some of the remaining infiltrate will percolate downward to the water table and flow with the groundwater. Ultimately, both of these sources may intercept a stream channel and contribute to the total runoff.

During a particular storm event, the contribution of runoff to a stream varies significantly through time. Inflow to the stream begins with direct channel precipitation followed by overland surface runoff when the appropriate conditions exist. Lateral interflow and groundwater contributions typically move more slowly and impact the stream level later. The groundwater portion of the runoff frequently supports the flow of a stream both during and between storm events.

See also Evaporation

S

Sagan, Carl (1934-1996)

American astronomer

One of the first scientists to take an active interest in the possibility that life exists elsewhere in the Universe, and an astronomer that was both a best-selling author and a popular television figure, Carl Sagan was one of the best-known scientists in the world. Sagan made important contributions to studies of Venus and Mars, and he was extensively involved in planning NASA's *Mariner* missions. Regular appearances on the *Tonight Show* with Johnny Carson began a television career that culminated in the series Sagan hosted on public television called *Cosmos*, seen in sixty countries by over 400 million people. He was also one of the authors of a paper that predicted drastic global cooling after a nuclear war; the concept of "nuclear winter" affected not only the scientific community, but also national and international policy, as well as public opinion about nuclear weapons and the arms race. Although some scientists considered Sagan too speculative and insufficiently committed to detailed scientific inquiry, many recognized his talent for explaining science, and acknowledged the importance of the publicity generated by Sagan's enthusiasm.

Sagan was born in Brooklyn, New York, the son of Samuel Sagan, a Russian emigrant and a cutter in a clothing factory, and Rachel Gruber Sagan. He became fascinated with the stars as a young child, and was an avid reader of science fiction, particularly the novels by Edgar Rice Burroughs about the exploration of Mars. By the age of five, Sagan was sure he wanted to be an astronomer, but, as he told Henry S.F. Cooper, Jr., of the *New Yorker*, he sadly assumed it was not a paying job; he expected he would have to work at "some job I was temperamentally unsuited for, like door-to-door salesman." When he found out a few years later that astronomers actually got paid, he was ecstatic. "That was a splendid day," he told Cooper.

Sagan's degrees, all of which he earned at the University of Chicago, include an A.B. in 1954, a B.S. in 1955, an M.S. in **physics** in 1956, and a doctorate in **astronomy** and astrophysics in 1960. As a graduate student, Sagan was deeply interested in the possibility of life on other planets, a discipline known as exobiology. Although this interest then was considered beyond the realm of responsible scientific investigation, he received important early support from scientists such as Nobel laureates Hermann Joseph Muller and Joshua Lederberg. He also worked with Harold C. Urey, who had won the 1934 Nobel Prize in chemistry and had been Stanley Lloyd Miller's thesis adviser when he conducted his famous experiment on the **origin of life**. Sagan wrote his doctoral dissertation, "Physical Studies of the Planets," under Gerard Peter Kuiper, one of the few astronomers at that time who was also a planetologist. It was during his graduate student days that Sagan met Lynn Margulis, a biologist, who became his wife in 1957. The couple had two sons before divorcing in 1963.

From graduate school, Sagan moved to the University of California at Berkeley, where he was the Miller residential fellow in astronomy from 1960 to 1962. He then accepted a position at Harvard as an assistant professor from 1962 to 1968. On April 6, Sagan married the painter Linda Salzman; Sagan's second marriage, which ended in a divorce, produced a son. From Harvard, Sagan went to Cornell University, where he was first an associate professor of astronomy at the Center for Radiophysics and **Space** Research. He was then promoted to professor and associate director at the center, serving in that capacity until 1977, when he became the David Duncan Professor of Astronomy and Space Science.

Sagan's first important contributions to the understanding of Mars and Venus began as insights while he was still a graduate student. Color variations had long been observed on the planet Mars, and some believed these variations indicated the seasonal changes of some form of Martian plant life. Sagan, working at times with James Pollack, postulated that the changing colors were instead caused by Martian dust, shifting through the action of **wind** storms; this interpretation was confirmed by *Mariner 9* in the early 1970s. Sagan also suggested that the surface of Venus was incredibly hot, since

Carl Sagan. *Library of Congress.*

the Venusian atmosphere of **carbon dioxide** and **water** vapor held in the sun's heat, thus creating a version of the "greenhouse effect." This theory was also confirmed by an exploring spacecraft, the Soviet probe *Venera IV*, which transmitted data about the atmosphere of Venus back to Earth in 1967. Sagan also performed experiments based on the work of Stanley Lloyd Miller, studying the production of organic molecules in an artificial atmosphere meant to simulate that of a primitive Earth or contemporary Jupiter. This work eventually earned him a patent for a technique that used gaseous mixtures to produce amino acids.

Sagan first became involved with spaceflight in 1959, when Lederberg suggested he join a committee on the Space Science Board of the National Academy of Sciences. He became increasingly involved with NASA (National Aeronautics and Space Administration) during the 1960s, and participated in many of their most important robotic missions. He developed experiments for the Mariner Venus mission and worked as a designer on the *Mariner 9* and the *Viking* missions to Mars, as well as on the *Pioneer 10*, the *Pioneer 11*, and the *Voyager* spacecrafts. Both the *Pioneer* and the *Voyager* spacecrafts have left our **solar system** carrying plaques which Sagan designed with Frank Drake as messages to any extraterrestrials that find them. The plaques contain pictures of two humans, a man and a woman, as well as various astronomical information. The nude man and woman were drawn by Sagan's second wife, Linda Salzman, and they provoked many letters to Sagan denouncing him for sending "smut" into space. During this project Sagan met the writer Ann Druyan, the project's creative director, who eventually became his wife. Sagan and Druyan had two children.

Sagan continued his involvement in space exploration in the 1980s and 1990s. The expertise he developed in biology and genetics while working with Muller, Lederberg, Urey, and others, is unusual for an astronomer, and he extensively researched the possibility that Saturn's **moon**, Titan, which has an atmosphere, might also have some form of life. Sagan was also involved in less direct searches for life beyond Earth. He was one of the prime movers behind NASA's establishment of a radio astronomy search program that Sagan called CETI, for Communication with Extra-Terrestrial Intelligence.

A colleague of Sagan's working on the Viking mission explained to Cooper of the *New Yorker* that this desire to find extraterrestrial life is the focus of all of Sagan's various scientific works. "Sagan desperately wants to find life someplace, anyplace—on Mars, on Titan, in the solar system or outside it. I don't know why, but if you read his papers or listen to his speeches, even though they are on a wide variety of seemingly unrelated topics, there is always the question 'Is this or that phenomenon related to life?' People say, 'What a varied career he has had,' but everything he has done has had this one underlying purpose." When Cooper asked Sagan why this was so, the scientist had a ready answer. "I think it's because human beings love to be alive, and we have an emotional resonance with something else alive, rather than with a molybdenum atom."

During the early 1970s Sagan began to make a number of brief appearances on television talk shows and news programs; Johnny Carson invited him on the *Tonight Show* for the first time in 1972, and Sagan soon was almost a regular there, returning to discuss science two or three times a year. However, it was *Cosmos*, which Public Television began broadcasting in 1980, that made him into a media sensation. Sagan narrated the series, which he wrote with Ann Druyan and Steven Soter, and they used special effects to illustrate a wide range of astronomical phenomena such as black holes. In addition to being extremely popular, the series was widely praised both for its showmanship and its content, although some reviewers had reservations about Sagan's speculations as well as his tendency to claim as fact what most scientists considered only hypotheses.

Sagan was actively involved in politics; as a graduate student, he was arrested in Wisconsin for soliciting funds for the Democratic Party, and he was also involved in protests against the Vietnam War. In December, 1983, he published, with Richard Turco, Brian Toon, Thomas Ackerman, and James Pollack, an article discussing the possible consequences of nuclear war. They proposed that even a limited number of nuclear explosions could drastically change the world's **climate** by starting thousands of intense fires that would throw hundreds of thousands of tons of smoke and ash into the atmosphere, lowering the average **temperature** ten to twenty degrees and bringing on what they called a "nuclear winter."

The authors happened upon this insight accidentally a few years earlier, while they were observing how **dust storms** on the planet Mars cooled the Martian surface and heated up the atmosphere. Their warning provoked a storm of controversy at first; their article was then followed by a number of studies on the effects of war and other human interventions on the world's climate. Sagan and his colleagues stressed that their predictions were only preliminary and based on certain assumptions about nuclear weapons and large-scale fires, and that their computations had been done on complex computer models of the imperfectly understood atmospheric system. However, despite numerous attempts to minimize the concept of a **nuclear winter**, the possibility that even a limited nuclear war might well lead to catastrophic environmental changes was supported by later research.

The idea of nuclear winter not only led to the reconsideration of the implications of nuclear war by many countries, institutions, and individuals, but it also produced great advances in research on Earth's atmosphere. In 1991, when the oil fields in Kuwait were burning after the Persian Gulf War, Sagan and others made a similar prediction about the effect the smoke from these fires would have on the climate. Based on the nuclear winter hypothesis and the recorded effects of certain **volcanic eruptions**, these predictions turned out to be inaccurate, although the smoke from the oil fires represented about 1% of the volume of smoke that would be created by a full-scale nuclear war.

In 1994, Sagan was diagnosed with myelodysplasia, a serious bone-marrow disease. Despite his illness, Sagan kept working on his numerous projects. His last book, *The Demon-Haunted World: Science as a Candle in the Dark*, was published in 1995. At the time of his death, Sagan was co-producing a film version of his novel *Contact*. His partner in this project was his wife, Ann Druyan, who had co-authored *Comet*. Released in 1997, the film received popular and critical acclaim as a testimony to Sagan's enthusiasm for the search for extraterrestrial life. Sagan, who lived in Ithaca, New York, died at the Fred Hutchinson Cancer Research Center in Seattle in 1996.

Carl Sagan won a Pulitzer Prize in 1978 for his book on **evolution** called *The Dragons of Eden*. He also won the A. Calvert Smith Prize (1964), NASA's Apollo Achievement Award (1969), NASA's Exceptional Scientific Achievement Medal (1972), NASA's Medal for Distinguished Public Service (twice), the International Astronaut Prize (1973), the John W. Campbell Memorial Award (1974), the Joseph Priestly Award (1975), the Newcomb Cleveland Prize (1977), the Rittenhouse Medal (1980), the Ralph Coats Roe Medal from the American Society of Mechanical Engineers (1981), the Tsiolkovsky Medal of the Soviet Cosmonautics Federation (1987), the Kennan Peace Award from SANE/Freeze (1988), the Oersted Medal of the American Association of Physics Teachers (1990), the UCLA Medal (1991), and the Mazursky Award from the American Astronomical Association (1991). Sagan was a fellow of the American Association for the Advancement of Science, the American Academy of Arts and Sciences, the American Institute for Aeronautics and Astronautics, and the American Geophysical Union. Sagan was also the chairman of the Division for Planetary Sciences of the American Astronomical Society (from 1975 to 1976) and for twelve years was editor-in-chief of *Icarus*, a journal of planetary studies.

SALT WEDGING

Salt wedging in an **estuary** is the process by which a distinct layer of **saltwater** forms below a layer of **freshwater** due to differences in density. Salt wedging is the result of weak tidal currents that cannot mix the saltwater with the freshwater, thus creating a halocline. Because freshwater is less dense than saltwater, it will float on top of the saltwater. A halocline is a zone in the **water** column where an abrupt alteration in the salinity creates a sharp freshwater-saltwater interface. Salt wedging typically occurs in an estuary along a salinity gradient when a fresh body of water such as a river meets, but does not mix with saltwater from an ocean or sea.

The rate of freshwater **runoff** from a river into an estuary is a major determinant of salt wedge formation. Salt wedging occurs when there is continuous flow of freshwater running into an estuary that opens into an ocean or sea with small tidal currents. Additionally, **evaporation** must be significantly lower than the freshwater runoff in order for salt wedging to occur.

Conversely, if there is no runoff of freshwater into the estuary, or if the runoff of freshwater is less than its evaporation, the salt water flowing in from the ocean will become more diluted within the estuary. Because the rate of evaporation is higher than the freshwater runoff, the top layer of water where evaporation occurs, will have a higher salinity than the other layers of the estuary.

Typically, the weak bottom current of a salt wedge estuary flows toward land while the dominant, turbulent current on the surface of the estuary flows toward sea. The horizontal layer where the two opposing currents meet creates internal waves that grow and eventually break as they move out toward sea, causing water to flow upward. The breaks in the internal waves shift diminutive volumes of saltwater from the bottom layer into the surface layer, causing the bottom layer to invariably flow towards land.

See also Hydrogeology; Tides

SALTATION

Saltation is the transportation of **sand** grains in small jumps by **wind** or flowing **water**. The term does not refer to salt, but is derived from the Latin *saltare*, to dance.

Certain conditions are necessary for saltation. First, a bed of sand grains must be covered by flowing air or water, as in a streambed or windy **desert**. Second, this flow must be turbulent. In turbulent flow, a fluid swirls and mixes chaotically—and virtually all natural flows of water and air are turbulent. Third, some of the eddies in the turbulence must be strong enough to lift individual sand grains from the bottom.

Fourth, the turbulence must not be so strong that grains cannot settle out again once suspended.

An individual saltating grain spends most of its time lying at rest on the bottom. Eventually an eddy happens to apply enough suction to the upper surface of the grain to overcome its weight, lifting it into the current. The grain is carried for a short distance, and then allowed to settle to the bottom again by the ever-shifting turbulence. After a random waiting period, the grain is lifted, carried, and dropped again, always farther downstream.

Grains too small to settle once suspended are carried indefinitely by the current; intermediate-size grains saltate; and grains too large to saltate either remain unmoved or move by sliding or rolling. Turbulent flow thus tends to sort grains by size.

See also Bed or traction load; Bedforms (ripples and dunes)

SALTWATER

Saltwater, or salt **water**, is a geological term that refers to naturally occurring solutions containing large concentrations of dissolved, inorganic ions. In addition, this term is often used as an adjective in biology, usually to refer to marine organisms, as in saltwater fish.

Saltwater most commonly refers to oceanic waters, in which the total concentration of ionic solutes is typically about 35 grams per liter (also expressed as 3.5%, or 35 parts per thousand). As a result of these large concentrations of dissolved ions, the density of saltwater (1.028 g/L at 4° C) is slightly greater than that of **freshwater** (1.00 g/L). Therefore, freshwater floats above saltwater in poorly mixed situations where the two types meet, as in estuaries and some underground reservoirs.

The ions with the largest concentrations in marine waters are sodium, chloride, sulfate, magnesium, calcium, potassium, and carbonate. In oceanic waters, sodium and chloride are the most important ions, having concentrations of 10.8 g/L and 19.4 g/L, respectively. Other important ions are sulfate (2.7 g/L), magnesium (1.3 g/L), and calcium and potassium (both 0.4 g/L). However, in inland saline waters, the concentrations and relative proportions of these and other ions can vary widely.

Other natural waters can also be salty, sometimes containing much larger concentrations of salt than the **oceans**. Some **lakes** and ponds, known as salt or brine surface waters, can have very large concentrations of dissolved, ionic solutes. These water bodies typically occur in a closed basin, with inflows of water but no outflow except by **evaporation**, which leaves salts behind. Consequently, the salt concentration of their contained water increases progressively over time. For example, the Great Salt Lake of Utah and the Dead Sea in Israel have salt concentrations exceeding 20%, as do smaller, saline ponds in Westphalia, Germany, and elsewhere in the world.

Underground waters can also be extremely salty. Underground saltwaters are commonly encountered in **petroleum** and gas well-fields, especially after the hydrocarbon resource has been exhausted by mining.

Both surface and underground saltwaters are sometimes “mined” for their contents of economically useful **minerals**.

Saltwater intrusions can be an important environmental problem, which can degrade water supplies required for drinking or irrigation. Saltwater intrusions are caused in places near the ocean where there are excessive withdrawals of underground supplies of fresh waters. This allows underground saltwaters to migrate inland, and spoil the quality of the **aquifer** for most uses. Saltwater intrusions are usually caused by excessive usage of ground water for irrigation in agriculture, or by excessive demands on freshwaters to supply drinking water to large cities.

See also Chemical bonds and physical properties; Hydrogeology; Water table; Weathering and weathering series

SALTWATER ENCROACHMENT

Saltwater encroachment or intrusion is the movement of saltwater into subsurface aquifers previously occupied by **freshwater**. Frequently, this occurs as freshwater from coastal aquifers is displaced as a result of the shoreward movement of seawater. Encroachment also occurs as the upconing of saltwater beneath pumping wells in areas where **groundwater** aquifers are underlain by more saline layers. In fact, the latter of these forms is quite common because two-thirds of the freshwater aquifers used for **water** supply in the United States are underlain by highly saline aquifers.

Because salt water contains dissolved **minerals**, its density is greater than that of freshwater. The lower density of fresh groundwater allows it to override or float on saltwater. As **precipitation** falls onto and infiltrates the land surface, freshwater accumulates in the ground above the saltwater in the shape of a lens. As more water is added through precipitation, the height of the **water table** above sea level is increased and the thickness of the freshwater lens also increases. Under certain conditions, the depth below sea level of the freshwater lens can extend to approximately 40 times the height of the water table above sea level. Along the lower curved boundary of the lens, some mixing of fresh and saltwater occurs due to movement of the interface by **tides** and other natural phenomena.

Saltwater encroachment occurs as a result of the withdrawal of fresh groundwater in the vicinity of saltwater. As freshwater is withdrawn from the ground, the pressure imposed on the saltwater by the overlying freshwater is reduced. This allows the saltwater/freshwater interface to migrate toward the point of withdrawals. The interface moves to a point where the pressure balance is restored. Lateral migration of the interface is most common in coastal locations whereas encroachment in areas overlying saline aquifers typically takes the form of an upward-pointing cone of saltwater directly beneath the pumping well.

Several methods have been examined for the control of saltwater encroachment. These techniques have included reduction of groundwater withdrawals, repositioning of withdrawal locations, utilization of recharge basins or injection wells to artificially maintain freshwater pressure, interception of intruding saltwater through a line of pumping wells parallel to the coastline, and emplacement of a subsurface groundwater barrier between the coastline and pumping wells. Reduction of groundwater withdrawals and relocation of pumping wells are the techniques found to be most effective and economically feasible in the control of saltwater encroachment.

See also Hydrologic cycle

SAN ANDREAS FAULT • *see* FAULTS AND FRACTURES

SAND

Sand is any material composed of loose, stony grains between 1/16 mm and 2 mm in diameter. Larger particles are categorized as gravel, smaller particles are categorized as silt or **clay**. Sands are usually created by the breakdown of rocks, and are transported by **wind** and **water**, before depositing to form soils, beaches, **dunes**, and underwater fans or deltas. Deposits of sand are often cemented together over time to form sandstones.

The most common sand-forming process is **weathering**, especially of **granite**. Granite consists of distinct **crystals** of **quartz**, **feldspar**, and other **minerals**. When exposed to water, some of these minerals (e.g., feldspar) decay chemically faster than others (especially quartz), allowing the granite to crumble into fragments. Sand formed by weathering is termed epiclastic.

Where fragmentation is rapid, granite crumbles before its feldspar has fully decayed and the resulting sand contains more feldspar. If fragmentation is slow, the resulting sand contains less feldspar. Fragmentation of **rock** is enhanced by exposure to fast-running water, so steep mountains are often source areas for feldspar-rich sands and gentler terrains are often source areas for feldspar-poor sands. Epiclastic sands and the sandstones formed from them thus record information about the environments that produce them. A sedimentologist can deduce the existence of whole mountain ranges long ago eroded, and of mountain-building episodes that occurred millions of years ago from sandstones rich in relatively unstable minerals like feldspar.

The behavior of sand carried by flowing water can inscribe even more detailed information about the environment in sand deposits. When water is flowing rapidly over a horizontal surface, any sudden vertical drop in that surface splits the current into two layers, (1) an upper layer that continues to flow downstream and (2) a slower backflow that curls under in the lee of the dropoff. Suspended sand tends to settle out in the backflow zone, building a slope called a “slip face” that tilts downhill from the dropoff. The backflow zone adds continually to the slip face, growing it downstream, and as the slip face grows downstream its top edge continues to create a backflow zone. The result is the deposition of a lengthening bed of sand. Typically, periodic avalanches of large grains down the slip face (or other processes) coat it with thin layers of distinctive material. These closely-spaced laminations are called “cross-bedding” because they angle across the main bed. Cross-bedding in **sandstone** records the direction of the current that deposited the bed, enabling geologists to map currents that flowed millions of years ago (paleocurrents).

Evidence of grain size, bed thickness, and cross-bedding angle, allows geologists to determine how deep and fast a paleocurrent was, and thus how steep the land was over which it flowed.

Ripples and dunes—probably the most familiar forms created by wind- or waterborne sand—involve similar processes. However, ripples and dunes are more typical of flow systems to which little or no sand is being added. The downstream slip faces of ripples and dunes are built from grains plucked from their upstream sides, so these structures can migrate without growing. When water or wind entering the system (e.g., water descending rapidly from a mountainous region) imports large quantities of sand, the result is net deposition rather than the mere migration of sandforms.

Grain shape, too, records history. All epiclastic grains of sand start out angular and become more rounded as they are polished by abrasion during transport by wind or water. Quartz grains, however, resist wear. One trip down a river is not enough to thoroughly round an angular grain of quartz; even a long sojourn on a beach, where grains are repeatedly tumbled by waves, does not suffice. The well-rounded state of many quartz sands can be accounted for only by crustal recycling. Quartz grains can survive many cycles of **erosion**, burial, cementation into sandstone, uplift, and re-erosion. Recycling time is on the order of 200 million years, so a quartz grain first weathered from granite 2.4 billion years ago may have gone through 10 or 12 cycles of burial and re-erosion to reach its present day state. An individual quartz grain’s degree of roundness is thus an index of its antiquity. Feldspar grains can also survive recycling, but not as well, so sand that has been recycled a few times consists mostly of quartz.

Sand can be formed not only by weathering but by explosive volcanism, the breaking up of shells by waves, the cementing into pellets of finer-grained materials (pelletization), and the **precipitation** of dissolved chemicals (e.g., calcium carbonate) from solution.

Pure quartz sands are mined to make **glass** and the extremely pure **silicon** employed in microchips and other electronic components.

See also Beach and shoreline dynamics; Bed or traction load; Bedding; Bedforms (ripples and dunes); Desert and desertification; Dune fields; Sedimentary rocks; Sedimentation

SANDSTONE

Any sedimentary **rock** composed of stony grains between 1/16 mm and 2 mm in diameter that are cemented together is a sandstone.

Sandstone forms from beds of **sand** laid down under the sea or in low-lying areas on the continents. As a bed of sand subsides into the earth's **crust**, usually pressed down by overlying sediments, it is heated and compressed. Hot **water** flows slowly through the spaces between the sand grains, importing dissolved **minerals** such as **quartz**, calcium carbonate, and **iron** oxide. These minerals crystallize around the sand grains and cement them together into a sandstone. Spaces remain between the grains, resulting in a porous, spongelike matrix through which liquids can flow.

Petroleum and **natural gas** are often found in sandstones. They do not form there, but seek to float to the surface by percolating through water-saturated sandstones. Sandstone layers shaped into domes by folding or other processes (and overlaid by non-porous rock) act as traps for migrating oil and gas, that ascend into them but then have no way out. Such traps are much sought after by oil companies; indeed, most sandstone sedimentologists work for the petroleum industry.

Another useful feature of sandstones is that they tend to record the surface conditions that prevailed when their sands were created and deposited. For example, the diagonal laminations often seen running across sandstone beds (cross-bedding) record the direction and speed of the water or **wind** that deposited their original sand. Furthermore, the ratio of **feldspar** to quartz in a sandstone reveals whether its sand was produced by rapid **erosion**, such as occurs in young, steep mountain ranges, or more slowly, such as occurs in flatter terrain. Since sand beds are often deposited rapidly by wind or water, tracks of reptiles—and even the pocks made by individual raindrops—may be preserved as **fossils** in sandstone.

A sandstone may be uplifted to the surface and broken down by **weather** into sand. This sand may be deposited in a bed that subsides, turns to sandstone, returns to the surface, breaks down into sand again, and so on. Some individual grains of sand have participated in more than 10 such cycles, each of which lasts on the order of 200 million years.

See also Bedding; Petroleum detection; Petroleum extraction; Sedimentary rocks; Sedimentation

SANTA ANNA WINDS • *see* SEASONAL WINDS

SATELLITE

In **astronomy**, a satellite refers to any object that is orbiting another larger, more massive object under the influence of their mutual gravitational force.

Thus, any planetary **moon** (e.g., the Moon revolving about Earth) is properly described as a satellite of that planet. Because the word is used to describe a single object, it is not used to designate rings of material orbiting a planet, even though such rings might be described as being made up of millions of satellites. In those rare instances where the mass of the satellite approaches that of the object around which it orbits, the system is sometimes referred to as a binary system. This is the reason that some people refer to Pluto and its moon Charon as a binary planet. This description is even more appropriate for some recently discovered **asteroids** which are composed of two similar sized objects orbiting each other.

In this century, scientific probes and commercial devices have been launched into Earth orbit or into orbits about the **Sun** or another planet. A tradition has developed to refer to these objects as man-made satellites to distinguish them from naturally occurring satellites. Surveillance satellites orbiting Earth have been used to measure everything from aspects of the planet's **weather** to movements of ships. Communications satellites revolve about Earth in geostationary orbits 25,000 mi (40,225 km) above the surface and a recent generation of navigation satellites and global positioning satellites (**GPS**) enables receiving stations on the surface of Earth to be determined with errors measured within a few meters.

Surveillance satellites have been placed in orbit about the Moon, Mars, and Venus to provide detailed maps of their surfaces and measure properties of their surrounding environment. A number of probes have at least temporarily entered the orbits of Jupiter, Saturn, or moons of these Jovian worlds.

Spacecraft missions to other planets in the **solar system** have revealed the existence of numerous previously unknown natural satellites and data from the **Hubble Space telescope** continue to reveal satellite objects that explain discrepancies in orbital paths and **rotation** rates of celestial bodies.

See also History of manned space exploration; Terra satellite and Earth Observing Systems (EOS); Weather forecasting methods

SATELLITE IMAGERY • *see* MAPPING TECHNIQUES

SATURATED ZONE

The saturated zone encompasses the **area** below ground in which all interconnected openings within the geologic medium are completely filled with **water**. Many hydrogeologists separate this zone into two subzones: the phreatic zone and the capillary fringe.

The phreatic zone is the area in which the interstitial water will freely flow from pores in the geologic material. Water in the pores of the phreatic zone is at a pressure greater than **atmospheric pressure**. Lying above, and separated from the phreatic zone by the **water table**, is the capillary fringe. Capillary action within the voids of the geologic medium causes water to be drawn upward from the top of the phreatic zone or captured as it percolates downward from the overlying **unsaturated zone**. Unlike the phreatic zone, however, the capillary action causes the water in the pores to have a pressure that is lower than atmospheric pressure. While the pores of both subzones are saturated, the different pressures in each cause the water to behave differently. Water within the phreatic zone will readily flow out of the pores while the negative pressures within the capillary fringe tightly hold the water in place. It is water from the phreatic zone that is collected and pumped from wells and flows into streams and **springs**.

Water within the phreatic portion of the saturated zone moves through the interconnected pores of the geologic material in response to the influences of **gravity** and pressure from overlying water. Rates of **groundwater** movement within the saturated zone ranges from a few feet per year to several feet per day depending upon local conditions. Only in larger fractures or karst systems do velocities approach those seen in surface flows.

The saturated zone extends downward from the capillary fringe to the depth where **rock** densities increase to the point that migration of fluids is impossible. In deep sedimentary basins, this may occur at depths of approximately 50,000 feet. At these extreme depths, the voids are no longer interconnected or not present.

Localized saturated zones can occur within the unsaturated zone when heterogeneities within the geologic medium cause differential downward percolation of water. Specifically, layers or lenses of low **permeability**, such as **clay** or shale, can retard the movement of water in the unsaturated zone and cause it to pool above the layer. This forms a perched zone of saturation.

See also Hydrogeology; Karst topography; Porosity and permeability

SATURN • *see* SOLAR SYSTEM

SCHIST

Schist is a **metamorphic rock** consisting of mineral grains that are more or less aligned in layers. Because of this structure, schist tends to cleave into flakes or slabs.

The parent **rock** of a schist may be igneous (e.g., **basalt**, **granite**, syenite) or sedimentary (e.g., **sandstone**, mudstone, impure **limestone**). The metamorphic grade of a schist depends on how thoroughly melted and recrystallized its parent rock has been; higher temperatures produce lower **water** content, coarser crystallization, more distinct layering, and reduced schistosity. At the high end of this scale, the schists blur into the gneisses.

The directional mineral structure of schists and gneisses arises during crystallization under anisotropic stress. Anisotropic stress is stress that does not point equally in all directions, such as would be produced by placing a block of any material on a table and leaning on it at an angle. During the formation of a schist or **gneiss**, the parent rock is heated sufficiently to mobilize its atoms. As it cools under anisotropic stress, its atoms assume the most stable, low-energy arrangements available to them: anisotropic **crystals** (plates or elongated shapes pointing in a common direction). Anisotropic crystal structure gives the schists their characteristic cleavage properties.

There are many varieties of schist. Two categories of particular importance are the greenschists and the blueschists. These have similar parent rocks but are formed under different pressure (P) and **temperature** (T) conditions. What **minerals** will crystallize during metamorphosis depend on both P and T. Greenschists form under high P and high T such as are found far below Earth's **crust**; blueschists form under high P and relatively *low* T. Both greenschists and blueschists are found in regionally metamorphosed landscapes—that is, land masses that have been submerged entirely in Earth's interior and metamorphosed in bulk. Regional metamorphosis often occurs at subduction zones, those places where one tectonic plate is being driven edgewise into the mantle beneath another. A large, cool chunk of Earth's crust takes a long time to reach ambient T when plunged into the mantle, but is raised to high P at once; a subducted mass that stays down long enough to achieve both high T and high P produces greenschist, while one that returns to the surface relatively quickly produces blueschist. One of the great unresolved puzzles of modern **geology** is that blueschist formation seems to have become globally more common in the last 300 million years, while greenschist formation has remained constant throughout Earth's history.

See also Metamorphism; Partial melting; Plate tectonics

SCHRÖDINGER, ERWIN (1887-1961)

Austrian physicist

Erwin Schrödinger shared the 1933 Nobel Prize for physics with English physicist Paul Dirac in recognition of his development of a wave equation describing the behavior of an electron in an **atom**. His theory was a consequence of French theoretical physicist Louis Victor Broglie's hypothesis that particles of matter might have properties that can be described by using wave functions. Schrödinger's wave equation provided a sound theoretical basis for the existence of electron orbitals (energy levels), which had been postulated on empirical grounds by Danish physicist **Niels Bohr** in 1913.

Schrödinger was born in Vienna, Austria. His father, Rudolf Schrödinger, enjoyed a wide range of interests, including painting and botany, and owned a successful oil cloth factory. Schrödinger's mother was the daughter of Alexander Bauer, a professor at the Technische Hochschule. For the first eleven years of his life, Schrödinger was taught at home. Though a tutor came on a regular basis, Schrödinger's most important instructor was his father, whom he described as a "friend, teacher, and tireless partner in conversation," as Armin Hermann quoted in *Dictionary of Scientific Biography*. From his father, Schrödinger also developed a wide range of academic interests, including not only mathematics and science but also grammar and poetry. In 1898, he entered the Akademische Gymnasium in Vienna to complete his pre-college studies.

Erwin Schrödinger. ***Library of Congress.***

Having graduated from the Gymnasium in 1906, Schrödinger entered the University of Vienna. By all accounts, the most powerful influence on him there was Friedrich Hasenöhrl, a brilliant young physicist who was killed in World War I a decade later. Schrödinger was an avid student of Hasenöhrl's for the full five years he was enrolled at Vienna. He held his teacher in such high esteem that he was later to remark at the 1933 Nobel Prize ceremonies that, if Hasenöhrl had not been killed in the war, it would have been Hasenöhrl, not Schrödinger, being honored in Stockholm.

Schrödinger was awarded his Ph.D. in physics in 1910, and was immediately offered a position at the University's Second Physics Institute, where he carried out research on a number of problems involving, among other topics, **magnetism** and dielectrics. He held this post until the outbreak of World War I, at which time he became an artillery officer assigned to the Italian front. As the War drew to a close, Schrödinger looked forward to an appointment as professor of theoretical physics at the University of Czernowitz, located in modern-day Ukraine. However, those plans were foiled with the disintegration of the Austro-Hungarian Empire, and Schrödinger was forced to return to the Second Physics Institute.

During his second tenure at the Institute, on April 6, 1920, Schrödinger married Annemarie Bertel, whom he had met prior to the War. Not long after his marriage, Schrödinger accepted an appointment as assistant to Max Wien in Jena, but remained there only four months. He then moved on to the Technische Hochschule in Stuttgart. Once again, he stayed only briefly—a single semester—before resigning his post and going on to the University of Breslau. He received yet another opportunity to move after being at the University for only a short time: he was offered the chair in theoretical physics at the University of Zürich in late 1921.

The six years that Schrödinger spend at Zürich were probably the most productive of his scientific career. At first, his work dealt with fairly traditional topics; one paper of particular practical interest reported his studies on the relationship between red-green and blue-yellow color blindness. Schrödinger's first interest in the problem of wave mechanics did not arise until 1925. A year earlier, de Broglie had announced his hypothesis of the existence of matter waves, a concept that few physicists were ready to accept. Schrödinger read about de Broglie's hypothesis in a footnote to a paper by American physicist **Albert Einstein**, one of the few scientists who did believe in de Broglie's ideas.

Schrödinger began to consider the possibility of expressing the movement of an electron in an atom in terms of a wave. He adopted the premise that an electron can travel around the nucleus only in a standing wave (that is, in a pattern described by a whole number of wavelengths). He looked for a mathematical equation that would describe the position of such "permitted" orbits. By January of 1926, he was ready to publish the first of four papers describing the results of this research. He had found a second order partial differential equation that met the conditions of his initial assumptions. The equation specified certain orbitals (energy levels) outside the nucleus where an electron wave with a whole number of wavelengths could be found. These orbitals corresponded precisely to the orbitals that Bohr had proposed on purely empirical grounds thirteen years earlier. The wave equation provided a sound theoretical basis for an atomic model that had originally been derived purely on the basis of experimental observations. In addition, the wave equation allowed the theoretical calculation of energy changes that occur when an electron moves from one permitted orbital to a higher or lower one. These energy changes conformed to those actually observed in spectroscopic measurements. The equation also explained why electrons cannot exist in regions between Bohr orbitals since only non-whole number wavelengths (and, therefore, non-permitted waves) can exist there.

After producing unsatisfactory results using relativistic corrections in his computations, Schrödinger decided to work with non-relativistic electron waves in his derivations. The results he obtained in this way agreed with experimental observations and he announced them in his early 1926 papers. The equation he published in these papers became known as "the Schrödinger wave equation" or simply "the wave equation." The wave equation was the second theoretical mechanism proposed for describing electrons in an atom, the first being German physicist Werner Karl Heisenberg's matrix mechanics. For most physicists, Schrödinger's approach was preferable since it lent itself to a physical, rather than strictly mathematical, interpretation. As it turned out, Schrödinger was soon able to show that wave mechanics and matrix mechanics are mathematically identical.

In 1927, Schrödinger was presented with a difficult career choice. He was offered the prestigious chair of theoretical physics at the University of Berlin left open by German physicist Max Planck's retirement. The position was arguably the most desirable in all of theoretical physics, at least in the German-speaking world; Berlin was the center of the newest and most exciting research in the field. Though Schrödinger disliked the hurried environment of a large city, preferring the peacefulness of his native Austrian Alps, he did accept the position.

Hermann quoted Schrödinger as calling the next six years a "very beautiful teaching and learning period." That period came to an ugly conclusion, however, with the rise of National Socialism in Germany. Having witnessed the dismissal of outstanding colleagues by the new regime, Schrödinger decided to leave Germany and accept an appointment at Magdalene College, Oxford, in England. In the same week he took up his new post he was notified that he had been awarded the 1933 Nobel Prize for physics with Dirac.

Schrödinger's stay at Oxford lasted only three years; then, he decided to take an opportunity to return to his native Austria and accept a position at the University of Graz. Unfortunately, he was dismissed from the University shortly after German leader Adolf Hitler's invasion of Austria in 1938, but Eamon de Valera, the Prime Minister of Eire and a mathematician, was able to have the University of Dublin establish a new Institute for Advanced Studies and secure an appointment for Schrödinger there.

In September, 1939, Schrödinger left Austria with few belongings and no money and immigrated to Ireland. He remained in Dublin for the next seventeen years, during which time he turned to philosophical questions such as the theoretical foundations of physics and the relationship between the physical and biological sciences. During this period, he wrote one of the most influential books in twentieth-century science, *What Is Life?* In this book, Schrödinger argued that the fundamental nature of living organisms could probably be studied and understood in terms of physical principles, particularly those of quantum mechanics. The book was later to be read by and become a powerful influence on the thought of the founders of modern molecular biology.

After World War II, Austria attempted to lure Schrödinger home. As long as the nation was under Soviet occupation, however, he resisted offers to return. Finally, in 1956, he accepted a special chair position at the University of Vienna and returned to the city of his birth. He became ill about a year after he settled in Vienna, however, and never fully recovered his health. He died in 1961, in the Alpine town of Alpbach, Austria, where he is buried.

Schrödinger received a number of honors and awards during his lifetime, including election into the Royal Society, the Prussian Academy of Sciences, the Austrian Academy of Sciences, and the Pontifical Academy of Sciences. He also retained his love for the arts throughout his life, becoming proficient in four modern languages in addition to Greek and Latin. He published a book of poetry and became skilled as a sculptor.

See also Quantum electrodynamics (QED); Quantum theory and mechanics

SCIENTIFIC DATA MANAGEMENT IN EARTH SCIENCES

Data constitute the raw material of scientific understanding. They are distinguished in analytical data (i.e. numbers with units) and meta-information (i.e. context describing analytical data). Data management is the control of data handling operations such as acquisition, analysis, quality check, processing, storage, retrieval, distribution, and sharing of data. However, it is not necessarily the generation and use of data. Data management ensures integrity of research, confidentiality, compliance with sponsor's requirements, and protects intellectual property. Scientific data management in Earth Sciences covers at least the four major fields of scientific activities, namely the geosphere, hydrosphere, atmosphere, and **biosphere**. Data cover time scales ranging from seconds to millions of millennia and provide baseline information for research in many disciplines, among them monitoring environmental changes—gradual or sudden, foreseen or unexpected, natural or man made.

Scientific data gathering has a long history, and evolved from descriptive cataloguing to a relational digital record of expertise. The Chinese chronicled information about solar and aurora activity in past millennia. In the eighteenth and nineteenth centuries, geological data were recorded in expedition reports. Since the middle of the twentieth century, inconceivably huge and heterogeneous numeric data loads came up during large-scale marine projects. At this time, a data management strategy termed 'the box of floppies' approach was developed. The data sets were supplied to the data center as discrete entities (usually on floppy disks) where they were checked, catalogued and stored. On demand, clients were supplied with the data sets necessary to satisfy their requirements. Data management philosophy in these scenarios was firmly focused on data archival. Today, the challenge of scientific data management is to provide standardized import and export routines to support the scientific community with comfortable and uniform retrieval functions and efficient tools for the graphical visualization of their analytical and meta-data through computers.

The unique requirement of data management in Earth Sciences compared to other (natural) sciences is that any datum has to be specified by a space-time geo-code, i.e., geographical (**latitude**, **longitude**, sample depth) and time dimensions (date/time, period of time, age [model]). Together with the key parameters sample compartment (e.g., **water** column, sediment), variable and unit, and principal investigator (i.e. the owner of a data series) any data collection can be mapped however heterogeneous it may be. To describe this so-called n-dimensional parameter catalogue, a meta-information catalogue was invented that comprises project fact, campaign information, station data, **scientific method**, public access status, and reference where the data were published first. Both parameter and meta-information catalogues itemize the analytical value and serve as unambiguous identifier. Validation and verification of data are the two most critical components in scientific data management. Even if scientific data are supposed to be correct, the definition of what is correct is far from straightforward. It can quite often be a matter of opinion, and opinions are subject to change as scientific knowledge changes. For example, the CLIMAP Project Members referred to the Last Glacial Maximum as "18k" (i.e., 18,000 years ago), whereas Bard revised this concept some 25 years later to "21,000 calendar years ago." Each datum reflects current scientific opinion at its time; however, it became subject to change with altered scientific knowledge. It is not essential to have only excellent quality data sets but it is important that exact information on the quality is provided. The user of a specific data set must be able to verify data by reading the reference publication and thus make a decision about the usefulness of retrieved data. Since (yet) unpublished data are even more sensitive than published data, the data management group is obliged to ensure that data are not accessed from outside a project until data are formally placed in public domain.

Consequently, a data management profile in Earth sciences seeks an information system that represents the n-dimensional parameter-catalogue and the accompanying meta-information catalogue by a suitable data model and archives the data collection in a way that any datum is described at any stage thoroughly and is traced back to its origin in order to protect copyright. Simultaneously, all interfaces are administered independently during data flow, i.e., from the scientific community to the data management, from the data management to the database, from the database to the data application (e.g., numerical model), from the application through the data management back to the scientific community. Finally, the archived data may be retrieved and presented as raw data and graphics. However, data format can be different each time. A popular conceptual construct of ideas applied to such an approach is the multidimensional view of data. This concept or data model, respectively, formally serves as a basis to inductively generate hypotheses with a search algorithm on specific data sets, which commonly is called data mining.

In practice, the conversion of multidimensional data model and data mining tool in Earth sciences is carried out by the International Council of Scientific Unions' World Data Center system (WDC). It works to guarantee access to any data in all fields of Earth sciences on a long-term basis. The categories of World Data Centers read like a *Who's Who* in Earth sciences: Air glow (Tokyo, Japan), **astronomy** (Beijing, China), atmospheric trace gases (Oak Ridge, United States), aurora (Tokyo, Japan), cosmic Rays (Toyokawa, Japan), Earth **tides** (Brussels, Belgium), geology (Beijing, China), geomagnetism (Copenhagen, Denmark; Edinburgh, United Kingdom; Kyoto, Japan; Mumbai, India), glaciology (Boulder, United States; Cambridge, United Kingdom; Lanzhou, China), human interactions in the environment (Palisades, United States), **ionosphere** (Tokyo, Japan), marine environmental sciences (Bremen, Germany), marine geology and geophysics (Boulder, United States; Moscow, Russia), **meteorology** (Asheville, United States; Beijing, China; Obninsk, Russia), nuclear radiation (Tokyo, Japan), **oceanography** (Obninsk, Russia; Silver Spring, United States; Tianjin, China), paleoclimatology (Boulder, United States), recent crustal movements (Ondrejov, Czech Republic), remotely sensed land data (Sioux Falls, United States), renewable resources and environment (Beijing, China), rockets and satellites (Obninsk, Russia), **rotation** of the Earth (Obninsk, Russia; Washington, United States), **satellite** information (Greenbelt, United States), **seismology** (Denver, United States; Beijing, China), soils (Wageningen, The Netherlands), solar activity (Meudon, France), solar radio emissions (Nagano, Japan), solar terrestrial **physics** (Boulder, United States; Didcot Oxon, United Kingdom; Moscow, Russia; Haymarket, **Australia**), solid Earth geophysics (Beijing, China; Boulder, United States; Moscow, Russia), **space** science (Beijing, China; Sagamihara, Japan), sunspot index (Brussels, Belgium).

Since the early beginnings of modern scientific data management in Earth sciences, the gathering and exchange of data has been transformed by rapid technological advances, such as the replacement of analog with digital instruments, the networking of digital instruments to simplify collection and exchange of data, unmanned automatic observatories etc. Personal computers and compact disc readers are ubiquitous. Many World Data Centers publish collections of digital data sets on compact discs for easy distribution. Digital communication networks make it possible to transfer large data files by electronic mail. Environmental disciplines make use of map-based data through Geographical Information Systems. The collaboration of international scientific bodies ensures the continuation of long-term monitoring of the Earth system, the permanent preservation of the data acquired for the mutual benefit of the international scientific community, and the dissemination mechanisms through publications, workshops, exhibitions, and other means.

See also GIS; Ice ages; International Council of Scientific Unions World Data Center System

SCIENTIFIC METHOD

Scientific thought aims to make correct predictions about events in nature. Although the predictive nature of scientific thought may not at first always be apparent, a little reflection usually reveals the predictive nature of any scientific activity. Just as the engineer who designs a bridge ensures that it will withstand the forces of nature, so the scientist considers the ability of any new scientific model to hold up under scientific scrutiny as new scientific data become available.

It is often said that the scientist attempts to understand nature. Ultimately, understanding something means being able to predict its behavior. Scientists, therefore, usually agree that events are not understandable unless they are predictable. Although the word "science" describes many activities, the notion of prediction or predictability is always implied when the word is used.

Until the seventeenth century, scientific prediction simply amounted to observing the changing events of the world, noting any regularities, and making predictions based upon those regularities. The Irish philosopher and bishop George Berkeley (1685–1753) was the first to rethink this notion of predictability.

Berkeley noted that each person experiences directly only the signals of his or her five senses. An individual can infer that a natural world exists as the source of his sensations, but he or she can never know the natural world directly. One can only know it through one's senses. In everyday life, people tend to forget that their knowledge of the external world comes to them through their five senses.

The physicists of the nineteenth century described the **atom** as though they could see it directly. Their descriptions changed constantly as new data arrived, and these physicists had to remind themselves that they were only working with a mental picture built with fragmentary information.

In 1913, **Niels Bohr** used the term *model* for his published description of the hydrogen atom. This term is now used to characterize theories developed long before Bohr's time. Essentially, a model implies some correspondence between the model itself and its object. A single correspondence is often enough to provide a very useful model, but it should never be forgotten that the intent of creating the model is to make predictions.

There are many types of models. A conceptual model refers to a mental picture of a model that is introspectively present when one thinks about it. A geometrical model refers to diagrams or drawings that are used to describe a model. A mathematical model refers to equations or other relationships that provide quantitative predictions.

New models are not constructed from observations of facts and previous models; they are postulated. That is to say, the statements that describe a model are assumed and predictions are made from them. The predictions are checked against the measurements or observations of actual events in nature. If the predictions prove accurate, the model is said to be validated. If the predictions fail, the model is discarded or adjusted until it can make accurate predictions.

The formulation of the scientific model is subject to no limitations in technique; the scientist is at liberty to use any method he can come up with, conscious or unconscious, to develop a model. Validation of the model, however, follows a single, recurrent pattern. Note that this pattern does not constitute a method for making new discoveries in science; rather it provides a way of validating new models after they have been postulated. This method is called the scientific method.

The scientific method 1) postulates a model consistent with existing experimental observations; 2) checks the predictions of this model against further observations or measurements; 3) adjusts or discards the model to agree with new observations or measurements.

The third step leads back to the second, so, in principle, the process continues without end. (Such a process is said to be recursive.) No assumptions are made about the reality of the model. The model that ultimately prevails may be the simplest, most convenient, or most satisfying model; but it will certainly be the one that best explains those problems that scientists have come to regard as most acute.

Paradigms are models that are unprecedented to attract an enduring group of adherents away from competing scientific models. A paradigm must be sufficiently open-ended to leave many problems for its adherents to solve. The paradigm is thus a theory from which springs a coherent tradition of scientific research. Examples of such traditions include Ptolemaic **astronomy**, Copernican astronomy, Aristotelian dynamics, Newtonian dynamics, etc.

To be accepted as a paradigm, a model must be better than its competitors, but it need not and cannot explain all the facts with which it is confronted. Paradigms acquire status because they are more successful than their competitors in solving a few problems that scientists have come to regard as acute. Normal science consists of extending the knowledge of those facts that are key to understanding the paradigm, and in further articulating the paradigm itself.

Scientific thought should in principle be cumulative; a new model should be capable of explaining everything the old model did. In some sense, the old model may appear to be a special case of the new model.

The descriptive phase of normal science involves the acquisition of experimental data. Much of science involves classification of these facts. Classification systems constitute abstract models, and it is often the case that examples are found that do not precisely fit in classification schemes. Whether these anomalies warrant reconstruction of the classification system depends on the consensus of the scientists involved.

Predictions that do not include numbers are called qualitative predictions. Only qualitative predictions can be made from qualitative observations. Predictions that include numbers are called quantitative predictions. Quantitative predictions are often expressed in terms of probabilities, and may contain estimates of the accuracy of the prediction.

The Greeks constructed a model in which the stars were lights fastened to the inside of a large, hollow sphere (the sky), and the sphere rotated about the earth as a center. This model predicts that all of the stars will remain fixed in position relative to each other. However, certain bright stars were found to wander about the sky. These stars were called planets (from the Greek word for wanderer). The model had to be modified to account for motion of the planets. In Ptolemy's (A.D. 100–170) model of the **solar system**, each planet moves in a small circular orbit, and the center of the small circle moves in a large circle around the earth as center.

Copernicus (1473–1543) assumed the **Sun** was near the center of a system of circular orbits in which the earth and planets moved with fair regularity. Like many new scientific ideas, Copernicus' idea was initially greeted as nonsense, but over time, it eventually took hold. One of the factors that led astronomers to accept Copernicus' model was that Ptolemaic astronomy could not explain a number of astronomical discoveries.

In the case of Copernicus, the problems of calendar design and astrology evoked questions among contemporary scientists. In fact, Copernicus's theory did not lead directly to any improvement in the calendar. Copernicus's theory suggested that the planets should be like the earth, that Venus should show phases, and that the universe should be vastly larger than previously supposed. Sixty years after Copernicus's death, when the **telescope** suddenly displayed mountains on the **moon**, the phases of Venus, and an immense number of previously unsuspected stars, the new theory received a great many converts, particularly from non-astronomers.

The change from the Ptolemaic model to the Copernican model is a particularly famous case of a paradigm change. As the Ptolemaic system evolved between 200 B.C. and 200 A.D., it eventually became highly successful in predicting changing positions of the stars and planets. No other ancient system had performed as well. In fact, the Ptolemaic astronomy is still used today as an engineering approximation. Ptolemy's predictions for the planets were as good as Copernicus's predictions. With respect to planetary position and precession of the equinoxes, however, the predictions made with Ptolemy's model were not quite consistent with the best available observations. Given a particular inconsistency, astronomers for many centuries were satisfied to make minor adjustments in the Ptolemaic model to account for it. Eventually, it became apparent that the web of complexity resulting from the minor adjustments was increasing more rapidly than the accuracy, and a discrepancy corrected in one place was likely to show up in another place.

Tycho Brahe (1546–1601) made a lifelong study of the planets. In the course of doing so, he acquired the data needed to demonstrate certain shortcomings in Copernicus's model. But it was left to **Johannes Kepler** (1571–1630), using Brahe's data after the latter's death, to come up with a set of laws consistent with the data. It is worth noting that the quantitative superiority of Kepler's astronomical tables to those computed from the Ptolemaic theory was a major factor in the conversion of many astronomers to the Copernican theory.

In fact, simple quantitative telescopic observations indicate that the planets do not quite obey Kepler's laws, and Isaac Newton (1642–1727) proposed a theory that shows why they should not. To redefine Kepler's laws, Newton had to neglect all gravitational attraction except that between individual planets and the sun. Since planets also attract each other, only approximate agreement between Kepler's laws and telescopic observation could be expected.

Newton thus generalized Kepler's laws in the sense that they could now describe the motion of any object moving in any sort of path. It is now known that objects moving almost as fast as the speed of light require a modification of Newton's laws, but such objects were unknown in Newton's day.

Newton's first law says that a body at rest remains at rest unless acted upon by an external force. His second law states quantitatively what happens when a force is applied to an object. The third law states that if a body A exerts a force F on body B, then body B exerts on body A a force that is equal in magnitude but opposite in direction to force F. Newton's fourth law is his law of gravitational attraction.

Newton's success in predicting quantitative astronomical observations was probably the single most important factor leading to acceptance of his theory over more reasonable but uniformly qualitative competitors.

It is often pointed out that Newton's model includes Kepler's laws as a special case. This permits scientists to say they understand Kepler's model as a special case of Newton's model. But when one considers the case of Newton's laws and relativistic theory, the special case argument does not hold up. Newton's laws can only be derived from Albert Einstein's (1876–1955) relativistic theory if the laws are reinterpreted in a way that would have only been possible after Einstein's work.

The variables and parameters that in Einstein's theory represent spatial position, time, mass, etc. appear in Newton's theory, and there still represent **space**, time, and mass. But the physical natures of the Einsteinian concepts differ from those of the Newtonian model. In Newtonian theory, mass is conserved; in Einstein's theory, mass is convertible with energy. The two ideas converge only at low velocities, but even then they are not exactly the same.

Scientific theories are often felt to be better than their predecessors because they are better instruments for solving puzzles and problems, but also for their superior abilities to represent what nature is really like. In this sense, it is often felt that successive theories come ever closer to representing truth, or what is "really there." Thomas Kuhn, the historian of science whose writings include the seminal book *The Structure of Scientific Revolution* (1962), found this idea implausible. He pointed out that although Newton's mechanics improve on Ptolemy's mechanics, and Einstein's mechanics improve on Newton's as instruments for puzzle solving, there does not appear to be any coherent direction of development. In some important respects, Professor Kuhn has argued, Einstein's general theory of relativity is closer to early Greek ideas than relativistic or ancient Greek ideas are to Newton's.

See also Historical geology; History of exploration I (Ancient and classical); History of exploration II (Age of exploration); History of exploration III (Modern era)

SCILLA, AGOSTINO (1629-1700)

Italian painter, paleontologist, and geologist

Agostino Scilla inaugurated the modern scientific study of **fossils**. Born the son of a minor government official in Messina, Sicily, he studied art in Messina under Antonio Ricci Barbalunga, who arranged for him to study in Rome for five years under Andrea Sacchi (1599–1661). Upon his return to Messina, Scilla associated with the Accademia della Fucina and established himself throughout eastern Sicily as a painter of religious scenes for church interiors, including some decorations for the cathedral in Syracuse. A gentleman of broad humanistic learning, with particular interest in ancient local culture, he became an expert on the history of Sicilian coins. During the 1650s or 1660s he began to study natural history, especially the fossils he found in the Sicilian hills. His expeditions were sometimes in company with the botanist Paolo Boccone (1633–1704). Scilla's training as a painter enhanced his skill at observation in general. He was intrigued by how the petrified forms of what looked like marine life could have come to rest at such high elevations so far from the sea.

Scilla's investigations of fossils culminated in the publication of his only scientific work, *La vana speculazione disingannata dal senso* (Vain Speculation Undeceived by Sense, 1670). In it, he famously opposed Francesco Stelluti (1577–1646) and Athanasius Kircher (1602–1680) on the question of why marine fossils are discovered inland. Stelluti, Kircher, and their allies believed that such fossils were "sports of nature," ruses of God to test our faith, or accidents explicable only through astrology, alchemy, or other fantastic means. To Scilla that was all nonsense. He wrote in plain language that he had no idea how the remains of corals, shells, shark teeth, and fish bones ended up in the hills, that he did not know of any method to try to learn how they got there, and that to speculate about their origin would be fanciful, unwarranted, and pointless. Scilla rejected the authority of ancient authors and medieval theologians, relying instead upon naturalistic observation, skeptical empiricism, and common sense. His style and degree of skepticism anticipated that of David Hume (1711–1776).

Prior to the work of Fabio Colonna (1567–1640), **John Ray** (1627–1705), Robert Hooke (1635–1703), Nicolaus Steno (1638–1686), and Scilla, there was no consensus that fossils were the remains of organic life. The *glossopetrae* ("tongue stones") commonly found throughout **Europe** were believed to have magical properties and mystic origins, by either the actions of lunar eclipses or the miracles of St. Paul. Unknown to each other, Steno and Scilla each positively identified *glossopetrae* as shark teeth. Their analysis of *glossopetrae* effectively undermined most earlier theories and superstitions about fossils.

In 1678, having participated in an unsuccessful Sicilian revolt against Spanish rule, Scilla was exiled. He went first to Turin, then, in 1679, to Rome, where he spent the rest of his life, making a living as a painter and becoming a prominent member of the Accademia di San Luca.

See also Fossil record; Fossils and fossilization; Marine transgression and marine recession; Sedimentary rocks; Sedimentation

SEAS • *see* OCEANS AND SEAS

SEA-FLOOR SPREADING

Earth's surface is composed of two kinds of **crust**, continental and oceanic. Most continental crust is over 3 billion years old, while virtually all oceanic crust is less than 180 million years old. Oceanic crust is young because it is continually destroyed in some places and created in others. Subduction is the process that destroys oceanic crust, and sea-floor spreading is the process that creates oceanic crust.

Sea-floor spreading is driven by crust formation along the **mid-ocean ridges**, meandering undersea mountain ranges that span Earth like the seams of a baseball. Oceanic crust is continually produced by **magma** welling up along the centerlines of the mid-ocean ridges. This new crust flows away from each ridgeline in two symmetric sheets, one on each side. The rate of sea-floor spreading resulting from this process is from 0.5 to 8 inches per year (1–20 cm/yr), depending on the particular mid-ocean ridge.

The Mid-Atlantic Ridge offers a particularly clear case of sea-floor spreading. About 165 million years ago, the Americas were matched to **Africa** and **Europe** like the pieces of a puzzle. Then, magma upwelling at the Mid-Atlantic Ridge began to produce oceanic crust, parting the continents to form the Atlantic Ocean. Today the Mid-Atlantic Ridge snakes down the center of the Atlantic all the way from Iceland to the Antarctic Plate and remains an active site of sea-floor spreading.

A dramatic proof of sea-floor spreading was discovered in the mid 1960s when data revealed alternating stripes of magnetic orientation on the sea floor, parallel to the mid-ocean ridges and symmetric across them—that is, a thick or thin stripe on one side of the ridge is always matched by a similar stripe at a similar distance on the other side. This mirror-image magnetic orientation pattern is created by steady sea-floor spreading combined with recurrent reversals of Earth's **magnetic field**. **Iron** atoms in liquid **rock** welling up along a mid-ocean ridge align with Earth's magnetic field. When this magma solidifies into crust, its iron atoms lock into position. This solid crust flows away from the mid-ocean ridge in both directions, carrying its original magnetic orientation with it. Eventually Earth's magnetic field reverses. Previously solidified crust retains its original field state, but crust just forming along the ridge is locked into the new orientation. As crust feeds steadily and symmetrically away from the ridgeline and Earth's magnetic field reverses over and over again, a symmetric striped pattern of **magnetism** is created.

See also Geographic and magnetic poles; Lithospheric plates; Magnetic field; Mantle plumes; Mapping techniques; Ocean trenches; Paleomagnetics; Plate tectonics

SEASONAL WINDS

A **wind** in low-latitude climates that seasonally changes direction between winter and summer is called a monsoon, and is a typical example of seasonal winds. Monsoons usually blow from the land in winter (called the dry phase, because it carries cool, dry air), and to the land in summer (called the wet phase, because it carries warm, moist air), causing a drastic change in the **precipitation** and **temperature** patterns of the **area**.

The word "monsoon" originates from the Arabic *mauzim*, meaning season. It was first used to depict the winds in the Arabian Sea, but later it was extended for seasonally changing wind systems all over the world. The main reason for monsoons is the difference in the heating of land and **water** surfaces, which results in land-ocean pressure differences. On a small scale, heat is transferred by land-sea breezes, to maintain the energy balance between land and water. On a larger scale, in winter when the air over the continents is colder than over the **oceans**, a large, high-pressure area builds up over

Siberia, resulting in air motion over the Indian Ocean and South China, causing dry, clear skies for East and South **Asia**. This is the winter monsoon. The opposite of this happens in summer; the air over the continents is much warmer than over the ocean, leading to moisture-carrying wind moving from the ocean towards the continent. When the humid air unites with relatively drier west airflow and crosses over mountains, it rises, reaches its saturation point, and thunderstorms and heavy showers develop. This is the summer monsoon in Southwest Asia—wind blowing from the ocean to the continent with wet, rainy **weather** patterns.

Although the most pronounced monsoon system is in eastern and southern Asia, monsoons can also be observed in West **Africa**, **Australia**, or the Pacific Ocean. Even in the southwestern United States, a smaller scale monsoonal circulation system exists (called North American Monsoon, Mexican monsoon, or Arizona monsoon). The North American Monsoon is a regional-scale circulation over southwest **North America** between July and September, bringing dramatic increases in rainfall in a normally arid region of Arizona, New Mexico, and northwestern Mexico. It is a monsoonal circulation because of its similarities to the original Southwest Asian monsoon—the west or northwest winds turn more south or southeast, bringing moisture from the Pacific Ocean, Gulf of California and **Gulf of Mexico**. As the moist air moves in, it is lifted up due to the mountains, which, combined with daytime heating from the **Sun**, causes thunderstorms.

The monsoon is an important feature of **atmospheric circulation**, because large areas in the tropics and subtropics are under the influence of monsoons, bringing humid air from over the oceans to produce rain over the land. In highly populated areas (e.g., Asia or India), this precipitation is essential for agriculture and food crop production. Sometimes a strong monsoon circulation can also bring flooding. Or, if the monsoon is late in a certain year, it can cause droughts.

A similar phenomenon to the monsoon also occurs in a smaller spatial and temporal scale, the mountain and valley breezes. The main reason they occur is also the difference in heating of the areas: during the day, the valley and the air around it warm and, because it is less dense, the air rises, and thus, a gentle upslope wind occurs. This wind is called the valley breeze. If the upslope valley winds carry sufficient moisture in the air, showers, even thunderstorms can develop in the early afternoon, during the warmest part of the day. The opposite happens at night, when the slopes cool down quickly, causing the surrounding air also to cool and glide down from the mountain to the valley, forming a mountain breeze (also called **gravity** winds or drainage winds). Although technically any kind of downslope wind is called a katabatic (or fall) wind, this term is usually used for a significantly stronger wind than a mountain breeze.

For katabatic winds carrying cold air, their ideal circumstances are mountains with steep downhill slopes and an elevated plateau. If winter snow accumulates on the plateau, it makes the surrounding air very cold, which then starts to move down as a cold, moderate breeze and can become a destructive, fast wind if it passes through a narrow **canyon** or channel. These katabatic winds have different names in different areas of the world. The bora is a northeast cold wind with speeds of sometimes more than 115 miles per hour (100 knots), blowing along the northern coast of the Adriatic Sea, when polar cold air from Russia moves down from a high plateau, reaching the lowlands. The mistral is a similar, although less violent cold wind in France, which moves down from the western mountains into the Rhone Valley then out to the Mediterranean Sea, often causing frost damage to vineyards. Even in Greenland and **Antarctica** there are occasional cold, strong katabatic winds.

Among the katabatic winds carrying warm air, the chinook wind is a dry warm wind, moving down the eastern slope of the Rocky Mountains in a narrow area between northeast New Mexico and Canada. When strong westerly winds blow over a north-south mountain, it produces low pressure on the eastward side of the mountain, forcing the air downhill, and causing a compressional heating. The chinook causes the temperature to rise over an area sharply, resulting in a sharp drop in the relative **humidity**. If chinooks move over heavy snow cover, they can even melt and evaporate a foot of snow in less than a day. The chinook is important because it can bring relief from a strong winter, uncovering grass, which can be fed to the livestock. A similar wind in the Alps is called foehn, a dry, warm wind descending the mountain slope then flowing across flat lands below. A warm and dry wind in South California blowing from the east or northeast is called the Santa Ana wind (named from the Santa Ana Canyon). Because this air originates in the **desert**, it is dry, and becomes even drier as it is heated. Brush fires and dried vegetation can follow the Santa Ana wind.

See also Air masses and fronts; Land and sea breeze

SEASONS

Seasons, which generally coincide with annual changes in **weather** patterns, are most pronounced in *temperate zones*. These zones extend from 23.5° north (and south) **latitude** to 66.5° north (and south) latitude. Within these latitudes, nature generally exhibits four seasons; spring, summer, autumn (or fall) and winter. Each season is characterized by differences in **temperature**, amounts of **precipitation**, and the length of daylight.

Seasonal observations have been noted in the earliest known written records of history. In fact, seasonal changes have affected the course of history in the outcomes of battles or movements of peoples in search of longer growing seasons has often been greatly influenced by seasonal changes. Spring comes from an Old English word meaning to rise; summer originated as a Sanskrit word meaning half year or season. Autumn comes originally from an Etruscan word for maturing. Winter comes from an Old English word meaning wet or **water**. The equatorial regions or torrid zones have no noticeable seasonal changes and one generally finds only a wet season and a dry season in these zones. In the polar regions the seasons are closely related to the amount of sunlight received, resulting in a light season and a dark season.

Seasons are tied to the apparent movements of the **Sun** and stars across the celestial sphere. In the Northern Hemisphere, spring begins at the vernal equinox (around March 21) when sunlight is directly incident on the equator with equal distribution of light to the Northern and Southern Hemispheres. Summer begins at the summer solstice (approximately June 21) when the Sun is at its apparent maximum declination. Autumn begins at the autumnal equinox around September 23, and winter at the winter solstice (minimum declination in the Northern Hemisphere) that occurs approximately December 21. Because every fourth year is a leap year and February then has 29 days, the dates of these seasonal starting points change slightly. In the Southern Hemisphere, the seasons are reversed with spring beginning in September, summer in December, fall in March, and winter in June. Seasons in the Southern Hemisphere are generally milder due to the moderating presence of larger amounts of ocean surface as compared to the Northern Hemisphere.

Changes in the seasons are caused by Earth's movement around the Sun. Because Earth orbits the Sun at varying distances, many people assume that the seasons result from the changes in the Earth-Sun distance. This belief is incorrect. In fact, Earth is actually closer to the Sun in January compared to June by approximately three million miles.

Earth makes one complete **revolution** about the Sun each year. The major reason that the seasons occur is that the axis of Earth's **rotation** is tilted with respect to the plane of its orbit. This tilt, called the obliquity of Earth's axis, is 23.5 degrees from a line drawn perpendicular to the plane of Earth's orbit. As Earth orbits the Sun, there are times of the year when the North Pole is alternately tilted toward the Sun (during northern hemispheric summer) or tilted away from the Sun (during northern hemispheric winter). At other times, the axis is generally perpendicular to the incoming Sun's rays. During summer, two effects contribute to produce warmer weather. First, the Sun's rays fall more directly on Earth's surface and this results in a stronger heating effect. The second reason for the seasonal temperature differences results from the differences in the amount of daylight hours versus nighttime hours. The Sun's rays warm Earth during daylight hours; Earth cools at night by re-radiating heat back into **space**. This is the major reason for the warmer days of summer and cooler days of winter. The orientation of Earth's axis during summer results in longer periods of daylight and shorter periods of darkness at this time of year. At the mid-northerly latitudes, summer days have about 16 hours of warming daylight and only eight hours of cooling nights. During mid-winter the pattern is reversed, resulting in longer nights and shorter days. To demonstrate that it is the daylight versus darkness ratio that produces climates that make growing seasons possible, one should note that even in regions only 30° from the poles one finds plants such as wheat, corn, and potatoes growing. In these regions the Sun is never very high in the sky but because of the orientation of Earth's axis, the Sun remains above the horizon for periods for over 20 hours a day from late spring to late summer.

Astronomers have assigned names to the dates at which the official seasons begin. When the axis of Earth is perpendicular to the incoming Sun's rays in spring the Sun stands directly over the equator at noon. As a result, daylight hours equal nighttime hours everywhere on Earth. This gives rise to the name given to this date, the vernal equinox. Vernal refers to spring and the word equinox means *equal night*. On the first day of fall, the autumnal equinox also produces 12 hours of daylight and 12 hours of darkness everywhere on Earth.

The name given for the first day of summer results from the observation that as the days get longer during the spring, the Sun's height over its noon horizon increases until it reaches June 21. Then on successive days, it dips lower in the sky as Earth moves toward the autumn and winter seasons. This gives rise to the name for that date, the summer solstice, because it is as though the Sun "stands still" in its noon height above the horizon. The winter solstice is likewise named because on December 21 the Sun reaches the lowest noon time height and appears to "stand still" on that date as well.

In the past, early humans celebrated the changes in the seasons on some of these cardinal dates. The vernal equinox was a day of celebration for the early Celtic tribes in ancient Britain, France, and Ireland. Other northern European tribes also marked the return of warmer weather on this date. Even the winter solstice was a time to celebrate, as it marked the lengthening days that would lead to spring. The ancient Romans celebrated the Feast of Saturnalia on the winter solstice. And even though there are no historical records to support the choice of a late December date for the birth of Christ, Christians in the fourth century A.D. chose to celebrate Christmas near the winter solstice.

See also Atmospheric circulation; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Latitude and longitude; Seasonal winds; Solar illumination: Seasonal and diurnal patterns

SEAWALLS AND BEACH EROSION

Beaches are one of the most important economic and environmental zones along coasts everywhere. In the United States alone, there are over 19,000 miles of beaches, 500 miles of which are within designated National Parks. Beaches are the boundaries between land and sea. A large part of the human population lives within driving distance of a beach. One of the recent environmental problems of importance is the increasing loss of beaches due to **erosion** of the shorelines.

Sediments, transported from inland resources, stock the rich supply of sands on beaches. **Rivers** drain inland valleys and plains and carry eroded particles from their source to their final deposition at sea. An enormous amount of **sand** and mud is carried by rivers such as the Nile and Mississippi. These rivers nourish farmers' lands and provide transport for economic goods. Because of their value, they are not often dammed, and their flow remains relatively unimpeded. However, unlike their famous counterparts, other rivers that feed coastal areas have been dammed in more than one place. The dams can provide everything from hydroelectric power to reservoirs for recreational and agricultural use.

The sediment load effect of large dams is often not observable until the river reaches the shore. The dams act as brakes for flowing **water**. When velocities are reduced, so is the carrying capacity of the river. Sediment loads are dumped on the upriver side of the dam. For local operators, the problem is one of continuously having to dredge the dams so the water can run through the turbines with the same force. For beaches, it is the reduction and even loss of sediment supply. The usual supply of sand is drastically reduced. Sand starvation occurs near the river mouths.

Another contributing factor to beach erosion is the loss of vegetation. The roots of plants keep sands in place. Shoreline plants are unique in that they have adapted to saltier conditions than their **freshwater** counterparts. When homes and business encroach on this delicate habitat the function they serve is lost. With increasing urbanization, more and more beach ecosystems are destroyed.

The Atlantic seaboard is an excellent example of a region that is battling beach erosion. Along the coast, a longshore current displaces the sand from the river source and down the coast. This current is referred to as littoral drift. Waves refract at often-steep angles off the shore and move sand from its original place to one a bit farther down the coast. Over time, the transport of sediment moves sand far away from the river mouths. It is deposited on beaches where it builds up into the shoreline. When sand supplies are decreased and the sediment loads are reduced, the waves continue to work away at the beach. They move sand in a daily cycle of littoral drift. Unfortunately, when the sand is reduced, the shorelines are eaten away by the longshore transport. For many this means the loss of sandy beaches and even the loss of homes.

Many types of remedies are attempted to reduce beach erosion. Some have had limited success while others appear to slow the erosion of sand. Some of the more long-lasting remedies are sea walls and jetties. Sea walls were designed to slow or reduce the impact of waves on the beach. They are built on top of and parallel to the beach. As waves come toward shore they first strike the sea wall and their energy is dissipated. When the waves finally reach the shore they are so weak that they carry hardly any sand away.

Another structure, the jetty, is built perpendicular to the beach. Jetties are walls of rocks or cement that jut out into the water. They are often constructed in groups. Their purpose is to control the flow of water along the shore and to sometimes block the movement of sand and sediment. Technically, a jetty keeps sand from moving to a certain location, such as a harbor, while a groin is a jetty that simply keeps sand from moving down the shore. When constructed in groups, groins are called groin fields. The fields buffer sand removal along the beach.

While certainly effective, none of these structures will ultimately end beach erosion. Increased awareness of the problem has teamed geologists with environmental scientists. Many alternate plans for saving beaches are being considered. Resuming the sediment flow is the ultimate solution, and remains an economic and technological challenge.

See also Beach and shoreline dynamics; Ocean circulation and currents; Sedimentation; Wave motions

SEDGWICK, REVEREND ADAM
(1785-1873)

English geologist and Anglican priest

Reverend Adam Sedgwick contributed to the entire scope of **geology**, but mainly toward defining the Cambrian stratum of the **fossil record** and trying to show precisely when life originated in **geologic time**. As an accomplished and popular teacher, speaker, and writer, he successfully encouraged many young British scientists and intellectuals to pursue geologic inquiry, and thus set the course of British geology for over a century. The Sedgwick Museum of Geology at the University of Cambridge is named in his honor.

Sedgwick was born the son of the Anglican vicar in Dent, Yorkshire, England. His childhood hobby of **rock** collecting on the moors grew into his career as a geologist. After his secondary education at Sedbergh School, he matriculated at Trinity College, Cambridge, where he received his baccalaureate in mathematics in 1808. He became a Fellow of Trinity College in 1810, was ordained in the Church of England in 1817, assumed the Woodwardian Chair of Geology at Cambridge in 1818, served as president of the Geological Society of London from 1829 to 1831, and after 1845 held a variety of high administrative posts at Cambridge. Liberal in both politics and theology, he led the fight to allow non-Anglicans to study at Trinity and was among the first professors at Cambridge to allow women into his classes. He never married, but spent the rest of his life as a faculty member at Trinity, and died in Cambridge.

Sedgwick's research centered on the **Paleozoic Era**. Influenced by William Conybeare (1787–1857), he studied British **limestone** and **sandstone** deposits, concentrating especially on the Devonian, and became an expert on the fossil record throughout England and Wales. He established the contemporary agenda for **stratigraphy** and frequently challenged the findings of other geologists, notably Roderick Impey Murchison (1792–1871) with regard to the Silurian.

In 1831, one of Sedgwick's students was Charles Darwin (1809–1882). They maintained a lifelong friendship, even after 1859, when the clergyman expressed his strong objections to Darwin's recently published *Origin of Species*. Sedgwick did not accept a literalist or creationist interpretation of the *Bible*, but, consistent with his opposition to Darwinian **evolution**, believed in the cataclysmic or catastrophic theory of the history of Earth, whereby occasional dramatic events cause mass extinctions and radically alter further geologic development. In this he supported **Georges Cuvier** (1769–1832) and opposed **Charles Lyell** (1797–1875), a major proponent of a theory of gradual, steady, predictable geologic change.

See also Evolution, evidence of; Evolutionary mechanisms; Fossils and fossilization

SEDIMENTARY ROCKS

Sedimentary rocks form at or near the earth's surface from the weathered remains of pre-existing rocks or organic debris. The term sedimentary **rock** applies both to consolidated, or lithified sediments (bound together, or cemented) and unconsolidated sediments (loose, like **sand**). Although there is some overlap, most sedimentary rocks belong to one of the following groups: clastic, chemical, or organic.

Mechanical **weathering** breaks up rocks, while chemical weathering dissolves and decomposes rocks. Weathering of igneous, metamorphic, and sedimentary rocks produces rock fragments, or clastic sediments, and mineral-rich **water**, or mineral solutions. After transport and laying down, or deposition, of sediments by **wind**, water, or **ice**, compaction occurs due to the weight of overlying sediments that accumulate later. Finally, **minerals** from mineral-rich solutions may crystallize, or precipitate, between the grains and act as cement. Cementation of the unconsolidated sediments forms a consolidated rock. Clastic rocks are classified based on their grain size. The most common clastic sedimentary rocks are shale (grains less than 1/256 mm in diameter), siltstone (1/256–1/16 mm), **sandstone** (1/16–2 mm), and conglomerate (greater than 2 mm).

Chemical or crystalline sedimentary rocks form from mineral solutions. Under the right conditions, minerals precipitate out of mineral-rich water to form layers of one or more minerals, or chemical sediments. For example, suppose ocean water is evaporating from an enclosed **area**, such as a bay, faster than water is flowing in from the open ocean. Salt deposits will form on the bottom of the bay as the concentration of dissolved minerals in the bay water increases. This is similar to putting salt water into a **glass** and letting the water evaporate; a layer of interlocking salt **crystals** will precipitate on the bottom of the glass. Due to their interlocking crystals, chemical sediments always form consolidated sedimentary rocks. Chemical rocks are classified based on their mineral composition. Rock salt (composed of the mineral halite, or table salt), rock **gypsum** (composed of gypsum), and crystalline **limestone** (composed of calcite) are common chemical sedimentary rocks.

Organic sedimentary rocks form from organically derived sediments. These organic sediments come from either animals or plants and usually consist of body parts. For example, many limestones are composed of abundant marine **fossils**, so these limestones are of organic rather than chemical origin. **Coal** is an organic rock composed of the remains of plants deposited in coastal swamps. The sediments in some organic rocks (for example, fossiliferous limestone) undergo cementation; other sediments may only be compacted together (for example, coal). Geologists classify organic rocks by their composition.

The origin (clastic, chemical, or organic) and composition of a sedimentary rock provide geologists with many insights into the environment where it was deposited. Geologists use this information to interpret the geologic history of an area, and to search for economically important rocks and minerals.

See also Depositional environments; Lithification; Mineralogy; Sedimentation; Stratigraphy

SEDIMENTATION

Sediments are loose Earth materials such as **sand** that accumulate on the land surface, in river and lakebeds, and on the ocean floor. Sediments form by **weathering** of **rock**. They then erode from the site of weathering and are transported by **wind**, **water**, **ice**, and **mass wasting**, all operating under the influence of **gravity**. Eventually sediment settles out and accumulates after transport; this process is known as deposition. Sedimentation is a general term for the processes of **erosion**, transport, and deposition. Sedimentology is the study of sediments and sedimentation.

There are three basic types of sediment: rock fragments, or clastic sediments; mineral deposits, or chemical sediments; and rock fragments and organic matter, or organic sediments. Dissolved **minerals** form by weathering rocks exposed at the earth's surface. Organic matter is derived from the decaying remains of plants and animals.

Clastic and chemical sediments form during weathering of **bedrock** or pre-existing sediment by both physical and chemical processes. Organic sediments are also produced by a combination of physical and chemical weathering. Physical (or mechanical) weathering—the disintegration of Earth materials—is generally caused by abrasion or fracturing, such as the striking of one pebble against another in a river or stream bed, or the cracking of a rock by expanding ice. Physical weathering produces clastic and organic sediment.

Chemical weathering, or the decay and dissolution of Earth materials, is caused by a variety of processes. However, it results primarily from various interactions between water and rock material. Chemical weathering may alter the mineral content of a rock by either adding or removing certain chemical components. Some mineral by-products of chemical weathering are dissolved by water and transported below ground or to an ocean or lake in solution. Later, these dissolved minerals may precipitate out, forming deposits on the roof of a **cave** (as **stalactites**), or the ocean floor. Chemical weathering produces clastic, chemical, and organic sediments.

Erosion and transport of sediments from the site of weathering are caused by one or more of the following agents: gravity, wind, water, or ice. When gravity acts alone to move a body of sediment or rock, this is known as mass wasting. When the forces of wind, water, or ice act to erode sediment, they always do so under the influence of gravity.

Large volumes of sediment, ranging in size from mud to boulders, can move downslope due to gravity, a process called mass wasting. Rock falls, landslides, and mudflows are common types of mass wasting. If you have ever seen large boulders on a roadway you have seen the results of a rock fall. Rock falls occur when rocks in a cliff face are loosened by weathering, break loose, and roll and bounce downslope. Landslides consist of rapid downslope movement of a mass of rock or **soil**, and require that little or no water be present. Mudflows occur when a hillside composed of fine-grained material becomes nearly saturated by heavy rainfall. The water helps lubricate the sediment, and a lobe of mud quickly moves downslope. Other types of mass wasting include **slump**, **creep**, and subsidence.

Water is the most effective agent of transport, even in the **desert**. When you think of water erosion, you probably think of erosion mainly by stream water, which is channelized. However, water also erodes when it flows over a lawn or down the street, in what is known as sheet flow. Even when water simply falls from the sky and hits the ground in droplets, it erodes the surface. The less vegetation that is present, the more water erodes - as droplets, in sheets, or as channelized flow.

Wind is an important agent of erosion only where little or no vegetation is present. For this reason, deserts are well known for their wind erosion. However, as mentioned above, even in the desert, infrequent, but powerful rainstorms are still the most important agent of erosion. This is because relatively few areas of the world have strong prevailing winds with little vegetation, and because wind can rarely move particles larger than sand or small pebbles.

Ice in **glaciers** is very effective at eroding and transporting material of all sizes. Glaciers can move boulders as large as a house hundreds of miles.

Generally, erosive agents remove sediments from the site of weathering in one of three ways: impact of the agent, abrasion (both types of mechanical erosion, or corrasion), or **corrosion** (chemical erosion). The mere impact of wind, water, and ice erodes sediments; for example, flowing water exerts a force on sediments causing them to be swept away. The eroded sediments may already be loose, or they may be torn away from the rock surface by the force of the water. If the flow is strong enough, **clay**, silt, sand, and even gravel, can be eroded in this way.

Sediments come in all shapes and sizes. Sediment sizes are classified by separating them into a number of groups, based on metric measurements, and naming them using common terms and size modifiers. The terms, in order of decreasing size, are boulder (>256 mm), cobble (256–64 mm), pebble (64–2 mm), sand (2-1/16 mm), silt (1/16–1/256 mm), and clay (<1/256 mm). The modifiers in decreasing size order, are very coarse, coarse, medium, fine, and very fine. For example, sand is sediment that ranges in size from 2 millimeters to 1/16 mm. Very coarse sand ranges from 2 mm to 1 mm; coarse from 1 mm to 1/2 mm; medium from 1/2 mm to 1/4 mm; fine from 1/4 mm to 1/8 mm; and very fine from 1/8 mm to 1/16 mm. Unfortunately, the entire classification is not as consistent as the terminology for sand - not every group includes size modifiers.

When particles are eroded and transported by wind, water, or ice, they become part of the transport medium's sediment load. There are three categories of load that may be transported by an erosion agent: dissolved load, **suspended load**, and bedload. Wind is not capable of dissolving minerals, and so it does not transport any dissolved load. The dissolved load in water and ice is not visible; to be deposited, it must be chemically precipitated.

Sediment can be suspended in wind, water, or ice. Suspended sediment is what makes stream water look dirty after a rainstorm and what makes a windstorm dusty. Suspended sediment is sediment that is not continuously in contact with the underlying surface (a stream bed or the desert floor) and so is suspended within the medium of transport. Generally, the smallest particles of sediment are likely to be suspended; occasionally sand is suspended by powerful winds and pebbles are suspended by floodwaters. However, because ice is a solid, virtually any size sediment can be part of the suspended sediment load of a glacier.

Bedload consists of the larger sediment that is only sporadically transported. Bedload remains in almost continuous contact with the bottom, and moves by rolling, skipping, or sliding along the bottom. Pebbles on a riverbed or beach are examples of bedload. Wind, water, and ice can all transport bedload, however, the size of sediment in the bedload varies greatly among these three transport agents.

Because of the low density of air, wind only rarely moves bedload coarser than fine sand. Some streams transport pebbles and coarser sediment only during **floods**, while other streams may, on a daily basis, transport all but boulders with ease.

Floodwater greatly increases the power of streams. For example, many streams can move boulders during flooding. Flooding also may cause large sections of a riverbank to be washed into the water and become part of its load. Bank erosion during flood events by a combination of abrasion, hydraulic impact, and mass wasting is often a significant source of a stream's load. Ice in glaciers, because it is a solid, can transport virtually any size material if the ice is sufficiently thick and the slope is steep.

For a particular agent of transport, its ability to move coarse sediments as either bedload or suspended load is dependant on its velocity. The higher the velocity, the coarser the load.

Transport of sediments causes them to become rounder as their irregular edges are removed by both abrasion and corrosion. Beach sand becomes highly rounded due to its endless rolling and bouncing in the surf. Of the agents of transport, wind is most effective at mechanically rounding (abrading) clastic sediments, or clasts. Its low density does not provide much of a "cushion" between the grains as they strike one another.

Sorting, or separation of clasts into similar sizes, also happens during sediment transport. Sorting occurs because the size of the grains that a medium of transport can move is limited by the medium's velocity and density. For example, in a stream on a particular day, water flow may only be strong enough to transport grains that are finer than medium-grained sand. So all clasts on the surface of the streambed that are equal to or larger than medium sand will be left behind. The sediment, therefore, becomes sorted. The easiest place to recognize this phenomenon is at the beach. Beach sand is very well sorted because coarser grains are only rarely transported up the beach face by the approaching waves, and finer material is suspended and carried away by the surf.

Ice is the poorest sorter of sediment. Glaciers can transport almost any size sediment easily, and when ice flow slows down or stops the sediment is not deposited due to the density of the ice. As a result, sediments deposited directly by ice when it melts are usually very poorly sorted. Significant sorting only occurs in glacial sediments that are subsequently transported by meltwater from the glacier. Wind, on the other hand, is the best sorter of sediment because it can usually only transport sediment that ranges in size from sand to clay. Occasional variation in wind speed during transport serves to further sort out these sediment sizes.

When the velocity (force) of the transport medium is insufficient to move a clastic (or organic) sediment particle it is deposited. When velocity decreases in wind or water, larger sediments are deposited first. Sediments that were part of the suspended load will drop out and become part of the bedload. If velocity continues to drop, nearly all bedload movement will cease, and only clay and the finest silt will be left suspended. In still water, even the clay will be deposited, over the next day or so, based on size—from largest clay particles to the smallest.

During its trip from outcrop to ocean, a typical sediment grain may be deposited, temporarily, thousands of times. However, when the transport medium's velocity increases again, these deposits will again be eroded and transported. Surprisingly, when compacted fine-grained clay deposits are subjected to stream erosion, they are nearly as difficult to erode as pebbles and boulders. Because the tiny clay particles are electrostatically attracted to one another, they resist erosion as well as much coarser grains. This is significant, for example, when comparing the erodibility of stream bank materials—clay soils in a river bank are fairly resistant to erosion, whereas sandy soils are not.

Eventually the sediment will reach a final resting place where it remains long enough to be buried by other sediments. This is known as the sediment's depositional environment.

Unlike clastic and organic sediment, chemical sediment cannot simply be deposited by a decrease in water velocity. Chemical sediment must crystallize from the solution; that is, it must be precipitated. A common way for **precipitation** to occur is by **evaporation**. As water evaporates from the surface, if it is not replaced by water from another source (rainfall or a stream) any dissolved minerals in the water will become more concentrated until they begin to precipitate out of the water and accumulate on the bottom. This often occurs in the desert in what are known as saltpans or **lakes**. It may also occur along the sea coast in a salt marsh.

Another mechanism that triggers mineral precipitation is a change in water **temperature**. When ocean waters with different temperatures mix, the end result may be seawater in which the concentration of dissolved minerals is higher than can be held in solution at that water temperature, and minerals will precipitate. For most minerals, their tendency to precipitate increases with decreasing water temperature. However, for some minerals, calcite (calcium carbonate) for example, the reverse is true.

Minerals may also be forced to precipitate by the biological activity of certain organisms. For example, when algae remove **carbon dioxide** from water the acidity of the water decreases, promoting the precipitation of calcite. Some marine organisms use this reaction, or similar chemical reactions, to promote mineral precipitation and use the minerals to form their skeletons. Clams, snails, hard corals, sea urchins, and a large variety of other marine organisms form their exoskeletons by manipulating water **chemistry** in this way.

Landscapes form and constantly change due to weathering and sedimentation. The **area** where sediment accumulates and is later buried by other sediments is known as its depositional environment. There are many large-scale, or regional, environments of deposition, as well as hundreds of smaller subenvironments within these regions. For example, **rivers** are regional **depositional environments**. Some span distances of hundreds of miles and contain a large number of subenvironments, such as channels, backswamps, **floodplains**, abandoned channels, and sand bars. These depositional subenvironments can also be thought of as depositional **landforms**, that is, landforms produced by deposition rather than erosion.

Erosion, weathering, and sedimentation constantly work together to reshape the earth's surface. These are natural processes that sometimes require us to adapt and adjust to changes in our environment. However, too many people and too much disturbance of the land surface can drastically increase sedimentation rates, leading to significant increases in the frequency and severity of certain natural disasters. For example, disturbance by construction and related land development is sometimes a contributing factor in the mudflows and landslides that occur in certain areas of California. The resulting damage can be costly both in terms of money and lives.

The world's rivers carry as much as 24 million tons of sediment to the ocean each year. About two-thirds of this may be directly related to human activity, which greatly accelerates the natural rate of erosion. This causes rapid loss of fertile topsoil, which leads to decreased crop productivity.

Increased sedimentation also causes increased size and frequency of flooding. As stream channels are filled in, the capacity of the channel decreases. As a result, streams flood more rapidly during a rainstorm, as well as more often, and they drain less quickly after flooding. Likewise, sedimentation can become a major problem on dammed rivers. Sediment accumulates in the lake created by the dam rather than moving farther downstream and accumulating in a **delta**. Over time, trapped sediment reduces the size of the lake and the useful life of the dam. In areas that are forested, lakes formed by dams are not as susceptible to this problem. Sedimentation is not as great due to interception of rainfall by the trees and underbrush.

Vegetative cover also prevents soil from washing into streams by holding the soil in place. Without vegetation, erosion rates can increase significantly. Human activity that disturbs the natural landscape and increases sediment loads to streams also disturbs aquatic ecosystems. Many state and local governments are now developing regulations concerning erosion and sedimentation resulting from private and commercial development.

SEEING

Astronomical seeing refers to the ability to view celestial objects through the obscurations of the earth's atmosphere. These obscurations include opacity, scattering, turbulence, atmospheric and thermal emission, and ionization.

Opacity refers to the fact that Earth's atmosphere is transparent only to relatively narrow wavelength ranges of light. These include visual light, the near infrared, microwaves and radio waves with wavelengths between about 0.35 mm and 1 m. The atmosphere is almost completely opaque to ultraviolet light, x rays, gamma rays, and radio waves with wavelengths greater than 1 m. The need to observe heavenly bodies outside of these narrow wavelength windows, along with the desirability to avoid the degrading affects of the atmosphere are among the main reasons for the development of space-based telescopes.

Ultraviolet photons are absorbed by electron transitions in **oxygen** and **ozone** atoms in the upper atmosphere. Because the amount of ozone varies greatly with location and seasonal time of year (e.g., the hole in the ozone layer over **Antarctica** during the winter) so does the amount of ultraviolet light reaching the surface of Earth. Ultraviolet light is mainly absorbed by molecular nitrogen. Infrared light is absorbed mainly by **water** vapor and **carbon dioxide** in the earth's atmosphere. Millimeter wavelengths are absorbed by rotational bands of water and molecular oxygen, while long radio waves are absorbed by ions high in the earth's atmosphere. Because 50% of the water vapor lies within three kilometers of the earth's surface, to some degree the infrared spectrum may be observed with instruments located on high mountains, or mounted on airplanes or balloons. Wavelength regions at which the atmosphere is transparent are called atmospheric windows.

Scattering of light particles degrades seeing. The mechanism by which molecules scatter visible light is called Rayleigh scattering, and the degree to which light is scattered is inversely proportional to the fourth power of the wavelength and proportional to the density of atmosphere. Thus, blue light is scattered more strongly than red light, accounting for the blue color of the sky. Red sunsets are an optical illusion caused by the intense scattering of blue light as the light rays travel through the horizon-level thickest regions of the atmosphere.

Atmospheric turbulence resulting from thermal currents, or **wind**, creates small changes in the density of pockets of air that cause the direction of light rays from point sources such as stars to be changed by refraction. In effect, the position of the star seems to shift slightly, and the star appears to twinkle. On a photographic plate, turbulence results in a smearing of the stellar image. Details of planetary features are often highly obscured and degraded by turbulence. The human eye, which processes light almost instantly, often sees a much sharper image than may be obtained with photographs.

Atmospheric emission of the night sky, also called airglow, is caused by the recombination of electrons with atoms that were ionized during the day by photochemical dissociation. This fluorescent light arises from neutral oxygen atoms and molecules, sodium, hydrogen, and hydroxide molecules, and is emitted about 100 km above the earth's surface. The total airglow over one arcsecond, roughly the apparent size of a star with a large **telescope**, corresponds to a visual magnitude of 22. Thus, stars dimmer than this, or galaxies with a surface **area** brightness less than this, are difficult to detect.

Thermal emission of the night sky is also a factor in the near infrared part of the spectrum. Any warm object in thermal equilibrium will emit black body radiation (e.g., **iron** heated to several hundred degrees will glow red or white). The earth's atmosphere below about 50 km emits a faint light by this mechanism, equivalent to a few Janskys (10^{-26} Watts/m^2Hz).

Ionization in the earth's **ionosphere** degrades radio waves. Turbulence in this layer of the atmosphere causes small fluctuations in the density of free electrons, which alter the direction of radio waves and cause dispersion in the frequencies of the radio waves. A radio wave emitted from a star of a particular wavelength or frequency will be dispersed into a small range of frequencies by ionization.

See also Astronomy; Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric pollution; Space and planetary geology

SEISMOGRAPH

A seismograph is an instrument used to measure and record ground vibration caused by explosions and **earthquake** shock waves. In the late 1800s, John Milne (1850–1913), an English mining engineer, developed the first precise seismometer, the sensor in a seismograph that detects and measures motion. Since then, seismograms, the data recorded by a seismograph, have helped seismologists predict much more than Earth movement. These devices have also led to discoveries about the nature of the earth's core.

The process of using a tool to detect ground motion dates back to the ancient Han Dynasty when Chang Heng, a first-century Chinese astronomer and mathematician, invented the first seismometer. He used a pendulum connected to an eight-spoked wheel in which each spoke was connected to a mounted dragon's head with moveable jaws. When the pendulum moved during an earthquake, a bronze ball in each of the heads would pop out if hit by the spoke of the pendulum wheel. While this did not lend clues about the force of an earthquake, it gave the ancient scientist an idea of the direction of the shock waves and their source. Since that time, Heng's concept has been refined considerably. Later seismographs employed a heavy pendulum with a *stylus*, or needle, suspended above a revolving drum. The drum contained a device on which the etchings from the needle could be recorded. During an earthquake, the pendulum and needle remained motionless while the drum on the base moved, recording the earth's movement. As much as these later pendulum seismographs improved upon the ancient Chinese method, they still fell short of providing answers to the many questions that arose with more precise readings. For example, once a strong motion set off a seismograph's pendulum, the pendulum would swing indefinitely, failing to record aftershocks that followed the initial disturbance. Additionally, the seismographs of the late 1800s recorded only a limited range of wave sizes and numbers. The inverted pendulum, invented by German seismologist Emil Weichert in 1899, helped overcome many of these limitations. Weichert employed a system of mechanical levers that linked the pendulum movement more closely to the earth's vibrations.

In 1906, Boris Golitsyn (1862–1916), a Soviet physicist and seismologist, devised the first electromagnetic seismograph; for the first time, a seismograph could be operated without mechanical levers. Although many of the modern seismographs are complicated technical devices, these instruments contain five basic parts. The clock records the exact time that the event takes place and marks the arrival time of each specific wave. The support structure, which is always securely attached to the ground, withstands the earth's vibrations during the earthquake or explosion. The inertial mass is a surface **area** that does not move although the earth and the support structure oscillate around it. The pivot holds the inertial mass in place, enabling it to record the earth's vibration. The vibrations are registered through the recording device: essentially a pen attached to the inertial mass and a roll of paper. The paper moves along with the earth's vibrations while the pen remains stationary. This shows the pattern of shock waves by recording thin, wavy lines, revealing the strength of the various waves as well as the frequency with which they occurred.

After the first modern seismograph was installed in the United States at the University of California at Berkeley, it recorded the 1906 earthquake that devastated San Francisco. Not long before that, Weichert and fellow scientist Richard Oldham (1858–1936) were finally able to determine the existence of the earth's core through precise recordings of seismic waves. In 1909, the use of a seismograph helped Yugoslavian seismologist and meteorologist Andrija Mohorovičic (1857–1936) discover the location at which the earth's **crust** meets the upper mantle. That discovery was followed in 1914 by Inge Lehmann's discovery of the boundary between the earth's outer and inner core. These important findings finally secured knowledge about the existence of boundaries for all of the earth's major layers: the inner core, the outer core, the mantle, and the crust. Seismographs also help miners determine the amount of dynamite needed for quarry blasts. Seismographs detect the force of atomic blasts and nuclear explosions, and are also used to detect the speed of seismic waves traveling in the earth. This data provides valuable information about the substances of which the earth is comprised, such as the natural resources oil and **coal**.

See also Earth, interior structure; Faults and fractures; Mohorovicic discontinuity (Moho); Richter scale

SEISMOLOGY

Seismology is the science that studies earthquakes and phenomena connected with them. Seismology is a branch of geophysics.

Seismology attempts to explain the origin of earthquakes, where, when, and why they occur, what accompanies them, and how to forecast them. Earthquakes were mentioned in written historical documents as early several thousands of years ago, but their serious study began only in the nineteenth century. As a rough guide, the **earthquake** is a vibration of the ground tangible in a definite place; the stronger these vibrations are, the more damage an earthquake can cause.

Two variables are usually used for describing the earthquake power: magnitude and intensity. Magnitude is an objective parameter, which is connected with the ground displacement at the point of its measurement; the bigger the displacement, the stronger is the earthquake. Earthquakes with magnitudes bigger than 5–6 are considered powerful ones. Intensity is a parameter that is not measured by a device. Different factors are taken into account to determine the intensity of an earthquake, and its value varies relative to locations accessed. The Modified Mercalli Intensity Scale determines earthquake intensity in the United States by gathering information, including witness accounts and building damage, and assigning a numeral scale from I (low intensity, no earth movement felt) to XII (visible earth movement seen, severe building damage).

The earth's **crust**, the upper layer of Earth's surface, consists of a solid medium with different values of parameters in different points, and is exposed to permanent action of different forces, which are also irregular. Action of these forces can lead to a situation in which some parts of the crust can occur under the condition of very high tension (for example, like a rod that is curved). If the tension remains too high, the crust is damaged in some points (the rod is broken). In this case, a very big amount of energy becomes free, and this energy transfers into elastic waves of different kinds, which can spread to great distances from the damage point. This illustrates a simplified model of an earthquake.

It is possible to distinguish the areas where earthquakes occur more often than in other places. Usually, these are mountain areas, and areas circumambient the Pacific (Japan, for example). Seismology studies these areas together with **geology**, in which during the late nineteenth century arose the special theory (**plate tectonics**) which explains a set of phenomena, in particular the occurrence of active seismic zones and non-active zones (platform regions). Earthquakes are practically nonexistent in non-active zones (for example, the Russian platform can be referred to as one of these regions).

Both seismology and geology use the achievements of **physics** (such as elasticity theory and hydrodynamics) in the creation of theories such as plate tectonics. In studying earthquakes, the oscillation theory and the theory of wave propagation in elastic media are used. The main devices used for earthquake study are seismometers, which record media oscillations at the point of the device location. Nowadays, such devices are located in many points on the earth's surface, on the ocean bottom, in shafts—often they are joined in special nets. The analysis of seismometers (seismograms), which take into account wave propagation theory, performs another important role; it permits scientists to understand deep-Earth structure. Even with improved theory, calculation methods, and equipment used in seismology, reliable forecasts of earthquakes still cannot be achieved.

Another important aspect of seismology is that its applied methods permit scientists to search useful **minerals**, especially oil. Seismologic methods also give the most precise results in underground nuclear tests control.

See also Earth, interior structure; Faults and fractures; Mid-ocean ridges and rifts; Mid-plate earthquakes; Petroleum detection; Richter scale; Subduction zone

SETI

SETI (The Search for Extraterrestrial Intelligence) is a term that encompasses several different groups and their efforts to seek out intelligent extraterrestrial life. The driving force behind these groups is the ancient human desire to understand the origin and distribution of life throughout the Universe. As technology progresses, SETI efforts move from the study of extraterrestrial rocks and meteors towards scanning the skies for a variety of signal types.

Cornell University professor Frank Drake founded the first SETI program in late 1959. Drake reinforced his idea of scanning the skies with his famous Drake Equation. The Drake Equation predicts the abundance of intelligent life within a certain galaxy.

The second major development of SETI took shape in the late 1960s when NASA joined the program. NASA was minimally involved the project, but spawned many SETI related programs. These programs included the Microwave Observing Project, Project Orion, the High Resolution Microwave Survey, Toward Other Planetary Systems, and more. One of the most intensive SETI related programs NASA would initiate began in 1992, but Congress cut funding for the program within a year. SETI projects now must rely on private funding, and SETI operates through the SETI Institute, a non-profit corporation.

The Very Large Array (VLA) is a collection of radio telescopes set up in a series, which turns the entire array into one vast radio telescope. *JLM Visuals. Reproduced by permission.*

Historically, scientists used several different methods for searching for extraterrestrial intelligence. The earliest method, and still most commonly used in present research, is the scanning of electromagnetic emissions. Radio waves are picked up by an array of radio telescopes and scanned for non-random patterns. More modern methods expand the search to other regions of the **electromagnetic spectrum**, including the infrared spectrum.

As of 2002, the University of California at Berkeley hosts the most widespread SETI effort in history. Berkeley projects include SETI@Home, SERENDIP, Optical SETI, and Southern SERENDIP. SETI@Home collects its data in the background of the Arecibo Radio Observatory and relays it back to the lab in Berkeley. The data is then divided into workunits and sent out to the personal computers of volunteers throughout the world. These personal computers scan the data for candidate signals. If a candidate signal appears, it is relayed back to Berkeley, where the signal is checked for data integrity. Finally, the lab removes radio interference and scans the data for final candidates. The Berkeley faction of SETI will be expanding their efforts with the Allen **Telescope** Array (formerly known as the One Hectare Telescope) designated specifically for this research.

Project Phoenix, also run by the SETI Institute, concentrates on obtaining signals from targeted areas within our galaxy. The focused Phoenix receiver can amass radio energy for longer periods of time and with greater sensitivity than previous SETI radio telescopes, allowing for faster and more precise analysis.

Although only a small fraction of the sky has been scanned, so far, SETI initiatives have not confirmed a signal from an extraterrestrial source that is conclusive proof of an extraterrestrial intelligence. A few strong and unexplained signals have intrigued SETI scientists; the most well known was received in 1977 at the Ohio State Radio Observatory. None of the signals have ever repeated.

SHARDS • *see* TUFF

SHEAR ZONES

Shear zones are microscopic to regional scale domains across which displacement has occurred. Brittle, brittle-ductile, or ductile deformation processes occur in shear zones at shallow, intermediate, or deep levels in the **crust**, respectively.

In brittle shear zones (equivalent to fault zones), displacement occurs on discrete fracture surfaces. In brittle-ductile shear zones, all or portions of the zone may undergo both ductile and brittle deformation. Displacement across brittle-ductile shear zones can be accommodated by oblique, en échelon stepping extensional veins (tension fractures) and/or shear fractures in addition to through-going shears parallel to zone boundaries. Extensional veins may be subsequently deformed into sigmoidal shapes (S shapes) and cut by younger veins. The sense of stepping of veins and their sigmoidal shape is used to determine the sense of displacement. **Folds** within transcurrent brittle-ductile shear zones (i.e., where displacement across steeply dipping shear zones is sub-horizontal) are en échelon stepping and doubly plunging. Fold axial surfaces initiated at approximately 45° to zone boundaries progressively rotate towards parallelism with the shear zone in areas of greatest deformation commonly overlying a crustal-scale structure.

Layers offset by ductile shear zones are thinned and progressively bent into parallelism with the zone. Grain size reduction in shear zones produces rocks called mylonites. The word mylonite is derived from the Greek word *mulon* or *mulos* for mill and the suffix *–ite*, for product of. Despite the origin of the word mylonite, only harder **minerals** such as **feldspar** are fractured and mechanically ground. Minerals such as **quartz** deform in a plastic manner instead, and are smeared out to form quartz ribbons. The term ultramylonite is used where grain size reduction has been extreme. The precursor **rock** type may be difficult to distinguish, e.g., ultramylonitic **granite**, **felsic** volcanic, and metasedimentary rock may all appear almost identical. Where the sense of offset of markers is not apparent, as is often the case in regional-scale ductile shear zones, the sense of displacement may be determined from observation of sections perpendicular to the foliation and parallel to the displacement direction (given by the orientation of mineral elongation lineations). This often requires microscopic, thin section examination. Shear criteria include:

- The relative orientations of flattening (S) and shear (C) foliations. S develops at about 45° to C, and is bent towards parallelism with C with increasing strain.
- Synthetic (C' or ecc1) shears at approximately 15–30° to C displace the shear foliation in mylonitic rocks with the same sense as the bulk shear sense. Antithetic shears (ecc2) with the opposite sense of displacement form at a large angle to the foliation.
- The asymmetry of foliations and strain (pressure) shadows around hard mineral grains or competent clasts. Low strain areas caused by ductile flow around rigid objects are sites where minerals (e.g., quartz, calcite, amphiboles, and biotite) crystallize. Mineral growths in strain shadows and surrounding foliations may be deformed when rigid objects rotate during shearing.
- Synthetic or antithetic slip on mineral cleavages. Slip and separation may occur in minerals such as pyroxene with pronounced mineral cleavage planes. Antithetic domino or bookshelf style slip occurs on planes inclined against the sense of shear at a large angle to the shear foliation. Cleavages inclined at small angles towards the sense of shear show synthetic slip.
- Mica fish (fish-shaped mica **crystals** whose extremities are asymmetrically bent into shear planes).
- X-ray, laser, or optical measurements of crystallographic axes provide shear criteria in quartz-rich mylonites.

Folds develop within ductile shear zones where layers are inclined to shear zone boundaries or are adjacent to irregularities that perturb ductile flow. Folds in ductile shear zones generally initiate with axes at a large angle to the displacement direction and are overturned in a sense consistent with the sense of shear. Care must, however, be taken in using fold asymmetry to establish the sense of shear. Folds in overturned layers at high strain within shear zones, and folds formed by the back-rotation of layers between two shear zones, may be overturned in a sense opposite to the sense of shear displacement. Fold axes progressively rotate towards the shear direction with progressive deformation. Folds with curved axes and sheath-like folds may form at high strains, producing complex, refolded folds within a single deformation event.

See also Faults and fractures; Plate tectonics

SHEPARD, ALAN B. (1923-1998)

American astronaut

One of the original seven American astronauts, Alan B. Shepard, Jr. became the first American to venture into **space** in a suborbital flight aboard the Mercury capsule, *Freedom 7*. His achievements—including his landmark *Freedom 7* flight on May 5, 1961—symbolized the beginning of a technological **revolution** in the 1960s and marked the onset of “new frontiers” in space. A decade later, he commanded the *Apollo 14* lunar mission, becoming the fifth man to step on the Moon’s surface and the only one of the original astronauts to make a flight to the **Moon**. In addition to his space flight accomplishments, Shepard served as Chief of the Astronaut Office and participated in the overall astronaut-training program. He received the National Aeronautics Space Administration

(NASA) Distinguished Service Medal from President John F. Kennedy for his Mercury flight. In 1971, appointed by President Nixon, he served as a delegate to the 26th United Nations General Assembly. He was promoted to rear admiral by the Navy in 1971, the first astronaut to achieve flag rank. In 1979, President Jimmy Carter awarded him the Medal of Honor for gallantry in the astronaut corps.

Alan Bartlett Shepard, Jr. was born in East Derry, New Hampshire, and spent most of his formative years in this New England setting. The son of a career military man—his father was an Army colonel—Shepard showed a strong interest at an early age for mechanical things, disassembling motors and engines and building model airplanes. He attended primary school in East Derry and received his secondary education from Pinkerton Academy in Derry in 1940. During high school, he did odd jobs at the local airport hangar in exchange for a chance to take airplane rides. There was little doubt in the family that Shepard would pursue a military career, and after completing a year's study at Admiral Farragut Academy in New Jersey, he entered the U.S. Naval Academy, graduating in 1944 with a B.S. in science. Shepard married Louise Brewer of Kennett Square, Pennsylvania; the couple eventually had two daughters.

Shepard's flying career began in 1947 after he served aboard the destroyer U.S.S. *Cogzwell* in the Pacific during the last year of World War II. He received flight training at both Corpus Christi, Texas, and Pensacola, Florida, receiving his wings in 1947. Between the years 1947 and 1950, he served with Fighter Squadron 42 at bases in Virginia and Florida, completing two cruises aboard carriers in the Mediterranean. In 1950, as a lieutenant, junior grade, he was selected to attend U.S. Navy Test Pilot School at Patuxent River in Maryland, serving two years in flight test work at that station. During those tours, he participated in high-altitude tests and experiments in the development of the Navy's in-flight refueling system. He was project test pilot on the F.S.D. *Skylancer* and was involved in testing the first angled deck on a U.S. Navy carrier. During his second tour to Patuxent for flight test work, the navy sent him to the Naval War College in Newport, Rhode Island. Upon graduation he became a staff officer at Atlantic Fleet Headquarters in Norfolk, in charge of aircraft readiness for the fleet. Being skipper of an aircraft squadron was a goal of any career pilot in the Navy and one that was of interest to Shepard. About this same time, NASA was developing Project Mercury and was seeking astronauts for America's space program.

Knowing that he met the required qualifications of NASA's advertised program, Shepard eagerly applied for a chance to serve his country and meet the challenge of the race to space. On April 27, 1959, NASA announced that Shepard and six other astronauts were selected as the first class of astronauts. A rigorous and intensive training program followed as preparations were being made for the first manned space flight. With the Russian space program forging ahead, it was imperative that a U.S. astronaut follow cosmonaut Yury Gagarin into space as soon as possible. Three astronauts—Shepard, Virgil "Gus" Grissom, and John Glenn—were selected to make three sub-orbital "up-and-down" missions to ready Mercury for orbital flight. Interest in the first manned American space flight was keen, forcing NASA to keep Shepard's identity secret until three days before the launch. At 9:45 A.M. on May 5th, 1961, Shepard, enclosed in the tiny bell-shaped Mercury capsule named *Freedom 7*, was thrust into space by a Redstone rocket to a distance of 2300 miles and a height of 113 miles above the surface of the Earth. The flight lasted only 15 minutes and 22 seconds and traveled at a speed of 5,180 mph. According to *Space Almanac*, Shepard, reporting from space that everything was "AOK," was in free-fall just five minutes before splashdown in the Atlantic Ocean. The U.S.S. *Lake Champlain* spotted his orange and white parachute 297 miles downrange from Cape Canaveral. Just before landing, the heat shield was dropped 4 feet, pulling out a rubberized landing bag designed to reduce shock. Shepard exclaimed "Boy what a ride," according to Tim Furniss in *Manned Spaceflight Log*, and with that successful, text-book perfect launch, NASA's space program gained support from the government and from people around the world.

Shepard's performance also showed the world the tradition of engineering excellence, professionalism and dedication that was evident in the subsequent missions. About ten weeks after this historic flight another Mercury-Redstone blasted Virgil Grissom's spacecraft for a similar flight. Shepard continued his training and space preparation and was selected for one of the early Gemini flights, but in early 1964, his career was sharply changed by an inner–ear ailment called Meniere's syndrome, which causes an imbalance and a gradual degradation of hearing. The Navy doctors would not let Shepard fly solo in jet planes, which forced NASA to ground him. The offer of a job as Chief of the Astronaut office with NASA came along about this time, and it helped allay some of the intense disappointment that Shepard experienced. As Chief, Shepard was in charge of all phases of the astronaut-training program and played an influential role in the selection of crews for upcoming missions. Periodic checks on his condition during this time showed a continued loss of hearing on the left side, and in May 1968, he submitted to an experimental operation to insert a plastic tube to relieve the pressure in his inner ear. After waiting six months for the final results of the operation, Shepard was declared by NASA officials and doctors fully fit to fly and to resume his role in the space flight program.

Shepard worked hard and long to ready himself for his next space endeavor, *Apollo 14*, which would last nine days and send a crew of three to the moon. The crew for this flight, Shepard as mission commander, Stuart Roosa as Command module pilot, and Edgar Mitchell as pilot of the lunar excursion module, was chosen in August 1969, just after the successful moon landing by *Apollo 11*. The mission was tentatively scheduled for an October 1970, launch date, but the explosion of the **oxygen** tank aboard *Apollo 13* called for several alterations in the *Apollo 14* spacecraft. One of the goals of this flight was to explore the Fra Mauro region of the Moon, and Shepard and Mitchell each spent more than 300 hours walking in **desert** areas and using simulators that resembled the lunar surface. A Saturn V rocket launched the

Apollo 14 capsule at 4:03 p.m. on January 3l, 1971. The astronauts had chosen the name *Kitty Hawk* as a tribute to the first manned powered flight in 1903, and named the lunar lander *Antares* for the star on which it would orient itself just before descending to the Fra Mauro landing site. *Apollo 14* entered lunar orbit on February 4, with touchdown in the uplands of the cone crater scheduled for the next day. Shepard and Mitchell departed from *Kitty Hawk* in *Antares* and descended smoothly to the surface, coming to rest on an 8 degree slope. Shepard descended the lander's ladder, stepping on the moon at 9:53 A.M., February 5, becoming the fifth man to walk on the moon. With much emotion, he reported to Houston, "I'm on the surface. It's been a long way, and I'm here," as quoted by Anthony J. Cipriano in *America's Journeys into Space*. He and Mitchell then collected 43 pounds of lunar samples and deployed TV, communications and scientific equipment in their first extra vehicular activity (EVA), which lasted 4 hours, 49 minutes. Their second EVA lasted 4 hours, 35 minutes, and the two astronauts used a Modularized Equipment Transporter for this landing. It was a rickshaw-like device in which they pulled their tools, cameras and samples with them across the moon. Shepard and Mitchell set off the first two moonquakes to be read by seismic monitors planted by earlier *Apollo* moonwalkers. As they prepared to leave the lunar surface in *Antares*, Shepard, an avid golfer, surprised his audience by making the first golf shot on the Moon, rigging a 6-iron club head to the end of a digging tool and hitting a ball hundreds of yards. On February 6, *Kitty Hawk* rocketed out of lunar orbit and headed for Earth. After nearly three days of coasting flight, *Apollo 14* splashed down in the Pacific Ocean, 4.6 miles from the recovery vessel *New Orleans*, on February 9—216 hours, 42 minutes after launch.

At Shepard's retirement from NASA and the U.S. Navy on August 1, 1974, Dr. James C. Fletcher, NASA Administrator, praised the astronaut's dedication and determination in a *NASA News* bulletin. "Al Shepard was the first American to make a space flight and his determination to overcome a physical ailment after his suborbital mission carried him to a highly successful manned lunar landing mission." Shepard joined the private sector as partner and chairman of the Marathon Construction Company of Houston, Texas. He became a successful businessman in Houston, pursuing interests as a commercial property developer, a venture capital group partner, and director of mutual fund companies. He also chaired the board of the Mercury Seven Foundation, created by the six living Mercury Seven astronauts and Grissom's widow to raise money for science and engineering scholarships. The Mercury capsule *Freedom 7* is on display at the National Air and Space Museum in Washington, D.C., and the *Apollo 14* command module *Kitty Hawk* is displayed at the Los Angeles County Museum in California. Shepard died in Houston at the age of 74.

See also Spacecraft, manned

SHOCK METAMORPHISM

Except for certain laboratory experiments and outdoor detonations of high explosives (including nuclear weapons), evidence of shock metamorphic conditions of extreme pressure and heat on Earth exist only within and around impact craters. Only hypervelocity impact between objects of substantial size moving at cosmic velocity (at least several kilometers per second) can produce these conditions. Meteorites larger than approximately 246 ft (75 m) in diameter, **asteroids**, and **comets** can pass through Earth's atmosphere and yet retain a very high percentage of their original velocity. In such events, this energy of motion is converted into seismic and heat energy almost instantaneously. On planetary bodies with no atmosphere, even smaller impacting bodies (even micrometeorites) can produce shock metamorphic effects. Meteorites recovered on Earth, which are fragments of larger bodies shattered by impact elsewhere in the **solar system**, also show shock metamorphic features and effects.

Shock **metamorphism** involves changes wrought by instantaneously applied extreme pressure and heat. This contrasts sharply with metamorphic changes accompanying development of most of Earth's metamorphic crustal rocks via long-term contact, cataclastic, and regional metamorphic conditions. Typical shock metamorphic pressures range from 72,519 to 14,503,774 psi (0.5 to 100 Gpa). Usually shock temperatures range from a few hundred to a few thousand degrees Fahrenheit or Celsius.

Shock metamorphism manifests itself through unique physical changes in mineral characteristics. There are five recognized shock stages, which are numbered 0, Ia, Ib, II, and III. **Quartz** (SiO_2), a very common mineral on Earth, displays a range of shock effects that make it one of the most studied **minerals** in shock metamorphism. At shock stage 0, Ia, and Ib, quartz displays progressively greater numbers of planar features (PFs), numbers of planar deformation features (PDFs), and extent of mosaicism. PFs form at threshold shock temperatures and pressures. PFs are microscopically thin fissures, spaced at about 20 microns or more, which are parallel to selected atomic planes within the quartz crystal. At higher temperatures and pressures, PFs give way to PDFs and mosaicism. PDFs are microscopic, parallel zones within the quartz cystal, spaced at 2–10 microns. PDFs are strongly planar and are arranged in specific crystallographic orientations. The number of PDFs and the specific orientation of PFs and PDFs are diagnostic of approximate levels of shock pressure. PFs and PDFs are found mainly in quartz, but also occur in some other silicate minerals as well. Mosaicism is a microscopic type of shock metamorphism in quartz and some other silicate minerals. It is an irregular, mottled pattern, as revealed under polarized light. Mosaicism is shock-induced expansion of crystal volume that results in multiple crystal development within the original (pre-shock) crystal.

At shock stages II and III, high-pressure forms (polymorphs) of pre-existing minerals and shock-produced melts can form. For quartz, the high-pressure polymorphs are stishovite and coesite, both SiO_2 like quartz, but with different internal structures of atoms (and higher densities). Other common minerals and their high-pressure polymorphs (in parentheses) are: **olivine** (ringwoodite); **plagioclase** (jadite); pyroxene (majorite); and **graphite** (lonsdaleite, a polycrystalline, impure **diamond**). For pressures over 60 gigapaschals, rocks can undergo complete **melting** and thus form impact melts. These melts may have very high temperatures (due to shock-wave passage); temperatures tend to be much higher than normal crustal processes or volcanic activity would produce. These extreme temperatures generate high-temperature polymorphs of common minerals such a lechatelierite (SiO_2, like quartz), which forms at temperatures over 3,092°F (1,700°C), and baddeleyite ($ZrSiO_4$, like zircon), which forms at temperatures over 3,452°F (1,900°C). Lechatelierite is not found in any other natural material, except fulgarites (fused **soil** or **sand** from **lightning** strikes). Impact melt **temperature** may exceed 18,000°F (10,000°C) and thus, pre-existing **rock** like **limestone**, which has a very high melting temperature, may become liquid. Rapid cooling of such melts produces various kinds of impact glassses.

See also Impact crater; Metamorphic rock

SIDEROPHILE • *see* CHALCOPHILES, LITHOPHILES, SIDEROPHILES, AND ATMOPHILES

SILICIC

Igneous rocks are classified by geologists using various schemes. One of the several schemes based on chemical composition divides igneous rocks into four categories according to silica (**silicon** dioxide, SiO_2) content: (1) Rocks containing more than 66% silica are silicic. (2) Rocks containing 52–66% silica are classified as intermediate. (3) Rocks containing 45–52% silica are **mafic**. (4) Rocks containing less than 45% silica are ultramafic.

Because silicon is less dense than the elements that often replace it in rock—especially **iron** and magnesium—silicic rocks are less dense than mafic rocks and tend to rise above them. The continents float on the mantle because they consist primarily of silicic rocks. Mafic and ultramafic rocks predominate in the mantle and oceanic **crust**.

All rocks high in **quartz**, which is simply crystalline silica, are silicic. **Feldspar** is a silicic mineral, and is a major component of many igneous rocks. Some common silicic rocks are **granite**, granodiorite, and **rhyolite**.

The terms silicic and siliceous (suh-LISH-us) are used synonymously by some geologists; others reserve silicic for high-silica igneous rocks, siliceous for high-silica **sedimentary rocks**. The term acid is sometimes used as a synonym for silicic and the terms basic and ferromagnesian as synonyms for mafic.

See also Isostasy

SILICON

Silicon (Si, element 14) is a nonmetallic chemical found in group IV, the **carbon** family, on the **Periodic table**. Swedish chemist Jons Jacob Berzelius first isolated and described the element in 1824.

In nature, silicon is always paired with another substance; it combines with **oxygen** to form **quartz** and **sand** (silicon dioxide, SiO_2) or with oxygen and a metal to form silicates, which are used to make **glass**, pottery, china, and other ceramics. The relatively inactive element occurs in nearly all rocks, as well as in **soil**, sand, and clays. It is the second most abundant element found in the earth's **crust**, surpassed only by oxygen.

Scientists create pure silicon by heating sand and coke in an electric furnace to remove oxide (oxygen) from the element. Pure silicon is colored dark gray and has a crystalline structure similar to **diamond**. The **crystals** are extremely hard and demonstrate remarkable insulating and semiconducting properties, which has made silicon an invaluable resource for the computing and electronics industries. A single purified silicon crystal contains millions of atoms accompanied by loosely attached electrons that break free upon the introduction of energy, such as light or heat. The flowing electrons conduct **electricity**, hence the term semiconductor. Today, silicon is the backbone of computer chips, transistors and many other electronic components.

Silicones, a chain of alternating silicon and oxygen atoms, are chemically inert and stable in the presence of high heat. The compounds are often used as lubricants, waterproofing materials and varnishes and enamels. Silicone gels have long been used as implants in the human body.

Silicon has an atomic weight of 28.086, a **melting** point of 2,570°F (1,410°C) and a boiling point of 4,270°F (2,355°C). Only three stable isotopes of silicon are known to exist: silicon-28, silicon-29 and silicon-30.

See also Earth (planet)

SILL

A sill is a formation of igneous **rock** found in features such as mesas, hogbacks, and cuestas. Although sills can become exposed, sills are formed underground and are thus composed of plutonic **igneous rocks**. Sills are an intrusive rock formation. Intrusive formations such as dikes and sills are formed from **magma** that solidifies beneath the Earth's surface and then intrudes into the overlying host or **country rock**.

Sills are distinguishable from the similarly formed dikes and dome forming laccoliths because sills are horizontal in orientation to the surface. Accordingly, sills are a horizontal intrusion.

Sills are sheet-like or tabular because the magma intrusion moves or intrudes horizontally before solidifying. Sills are characterized as concordant intrusive contacts. Because sills are an intrusive rock formation in contact with the host or country rock in the horizontal plane, they are often parallel to foliation or **bedding** planes (e.g., parallel to underlying sedimentary bedding planes). Sills form as rising magma encounters vertical resistance from host rock. The upwelling magma then spreads out in the horizontal plane into **area** of lower resistance to form sheet-like layers of rock.

Sill texture is a function of the time it takes for the magma to cool and solidify. Sills range from **aphanitic** to phaneritic in texture. In general, the longer the time to cool, the greater the extent and size of crystal formation. If a sill cools quickly, the texture is usually smooth and mineral **crystals** are not visible to the naked eye (aphanitic in texture). If conditions in the surrounding host rock are such that the magma cools over a long period of time, large visible crystals form a phaneritic texture.

When sills come to overlie sedimentary basins, the sills can act as horizontal obstructions that cap traps or reservoirs containing hydrocarbon **fuels**.

See also Dike; Petroleum detection; Pluton and plutonic bodies; Stratigraphy

SILT • *see* ROCK

SILURIAN PERIOD

In **geologic time**, the Silurian Period, the third period of the **Paleozoic Era**, covers the time from roughly 440 million years ago (mya) until 410 mya. The name, Silurian, derives from the Silures, an ancient British tribe. The Silurian Period spans two epochs. The Early Silurian Epoch is the most ancient, followed by the Late Silurian Epoch.

The Early Silurian Epoch is divided chronologically (from the most ancient to the most recent) into the Llandoverian and Wenlockian stages. The Late Silurian Epoch is divided chronologically (from the most ancient to the most recent) into the Ludlovian, and Pridolian stages.

In terms of paleogeography (the study of the **evolution** of the continents from **supercontinents** and the establishment of geologic features), the Silurian Period featured cleavage of some supercontinent landmass and fusion of plates into Laurussia. Collision with remnants of other continents later formed the supercontinent Laurasia and eventually the supercontinent Pangaea.

The **fossil record** establishes that the preceding **Ordovician Period** ended with a mass extinction. This mass extinction, approximately 440 mya, marked the end of the Ordovician Period and the start of the Silurian Period. In accord with a mass extinction, many fossils dated to the Ordovician Period are not found in Silurian Period formations. Differentiated by fossil remains and continental movements, the **Devonian Period** followed the Silurian Period.

The Silurian Period marked a geologically active period for volcanic activity. The accompanying ash deposits and **lava** flows are clearly evident in Silurian Period strata.

The fossil record indicates that it was during the Silurian Period that marine species made the evolutionary transition to terrestrial (land-based species). The first true insect fossils date to this period, as do fossils of jawed fish. Atmospheric changes, driven by increasingly diverse plant life, allowed the further development of the protective ozone layer, which filters out harmful ultraviolet radiation.

See also Archean; Cambrian Period; Cenozoic Era; Cretaceous Period; Dating methods; Eocene Epoch; Evolution, evidence of; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Miocene Epoch; Mississippian Period; Oligocene Epoch; Paleocene Epoch; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Tertiary Period; Triassic Period

SINKHOLES

Sinkholes are cavities that form when **water** erodes easily dissolved, or soluble, **rock** located beneath the ground surface. Water moves along joints, or fractures, enlarging them to form a channel that drains sediment and water into the subsurface. As the rock erodes, materials above subside into the openings. At the surface, sinkholes often appear as bowl-shaped depressions. If the drain becomes clogged with rock and **soil**, the sinkhole may fill with water. Many ponds and small **lakes** form via sinkholes.

Abundant sinkholes as well as caves, disappearing streams, and **springs**, characterize a type of landscape known as **karst topography**. Karst **topography** forms where **groundwater** erodes subsurface carbonate rock, such as **limestone** and **dolomite**, or evaporite rock, such as **gypsum** and halite (salt). **Carbon dioxide** (CO_2), when combined with the water in air and soil, acidifies the water. The slight acidity intensifies the corrosive ability of the water percolating into the soil and moving through fractured rock.

Geologists classify sinkholes mainly by their means of development. Collapse sinkholes are often funnel shaped. They form when soil or rock material collapses into a **cave**. Collapse may be sudden and damage is often significant; cars and homes may be swallowed by sinkholes.

Solution sinkholes form in rock with multiple vertical joints. Water passing along these joints expands them, allowing cover material to move into the openings. Solution sinkholes usually form slowly and minor damage occurs, such as cracking of building foundations.

Alluvial sinkholes are previously exposed sinkholes that, over time, partly or completely filled with Earth material. They can be hard to recognize and some are relatively stable.

Rejuvenated sinkholes are alluvial sinkholes in which the cover material once again begins to subside, producing a growing depression.

Uvalas are large sinkholes formed by the joining of several smaller sinkholes. Cockpits are extremely large sink-

Sinkholes can appear without warning, swallowing roads, cars, or in this case, a lake. ***© Fletcher W.K., 1982/Photo Researchers, Inc. Reproduced by permission.***

holes formed in thick limestone; some are more than a kilometer in diameter.

Sinkholes occur naturally, but are also induced by human activities. Pumping water from a well can trigger sinkhole collapse by lowering the **water table** and removing support for a cave's roof. Construction over sinkholes can also cause collapse. Sinkhole development may damage buildings, pipelines and roadways. Damage from the Winter Park sinkhole in Florida is estimated at greater than $2 million. Sinkholes may also serve as routes for the spread of contamination to groundwater when people use them as refuse dumps.

In areas where evaporite rock is common, human activities play an especially significant role in the formation of sinkholes. Evaporites dissolve in water much more easily than carbonate rocks. Salt mining and drilling into evaporite deposits allows water that is not already saturated with salt to easily dissolve the rock. These activities have caused the formation of several large sinkholes.

Sinkholes occur worldwide, and in the United States are common in southern Indiana, southwestern Illinois, Missouri, Kentucky, Tennessee, and Florida. In areas with known karst topography, subsurface drilling or geophysical **remote sensing** may be used to pinpoint the location of sinkholes.

See also Hydrogeology; Hydrologic cycle; Landscape evolution; Weathering and weathering series

SLATE

Slate is a hard, fine-grained **metamorphic rock** that forms when **sedimentary rocks**, such as shale and mudstone, are subjected to relatively low **temperature** and pressure. It occurs chiefly among older rocks. Millions of years of geological compression force the flaky **minerals** (mica, chlorite, **quartz**) within **clay** sediments to shift perpendicular to the pressure. This pushing alters the material's fundamental structure and creates a new feature known as slaty cleavage. True slate splits easily along this plane into thin, but durable, sheets.

While slate's characteristic color is gray-blue, varieties range from dark gray to black. Organic materials present in the parent **rock** can create different tinges. **Iron** oxide creates a reddish purple tinge; chlorite turns slate green. The rock also varies greatly in surface texture and luster; some slates have a dull, matte finish while others can be as shiny as mica.

Better grades of the rock are widely used for roofing, flooring and sidewall cladding. Slate is also used to make blackboards and pool tables. Pennsylvania and Vermont serve as the principal slate producers for the United States, although slate mines can also be found in Maine, Georgia, Lake Superior, and the Rocky Mountains.

See also Bedding; Metamorphism; Sedimentation

SLEET • *see* PRECIPITATION

SLUMP

The word slump is most commonly used as a colloquial description of a **landslide** with a markedly curved and concave-upward slip surface, which results in rotational movement of the mass above the slip surface. This stands in contrast to landslides with more nearly planar slip surfaces, above which the sliding motion is predominantly translational rather than rotational. Most landslides exhibit both kinds of motion, so the distinction is based on the predominant type of motion. Rotational slides tend to occur in slopes that are, at least mechanically speaking, relatively homogeneous whereas translational slides tend to occur in slopes that contain mechanical discontinuities such as steeply dipping **bedding** or soil-bedrock contacts that can evolve into slip surfaces.

Like the term mudslide, slump is frequently used but is not defined in the classification system used by most landslide specialists. Depending on the type of earth material involved, a slump can be properly described as a **rock** slide, debris slide, or earth slide with predominantly rotational movement.

The curved slip surface and resulting **rotation** of the material in a slump cause strata within a slump mass to be tilted backwards relative to undeformed strata beneath the slip surface. This back-tilting can produce a topographic depression that collects **water** and sediment, which can be used as a criterion to identify old slumps in the field. The material within a slump mass is in most cases remarkably undeformed, albeit rotated, which is a characteristic that distinguishes slides from flows.

A less common use of the term slump is in reference to the downslope flow of unlithified submarine sediments, which frequently occurs along topographic concavities such as submarine canyons. In this case the phenomenon would in most cases be properly described as a submarine debris or earth flow rather than a slide.

As is the case for all landslides, slumping begins when there is an imbalance between resisting and driving forces in a potentially unstable slope. If the slip surface is very nearly circular (as opposed to curved but non-circular), which is an idealized situation that does not often occur, stability can be assessed by comparing resisting and driving moments acting about a center of rotation. The resisting force (or moment) is a function of the shear strength of the **soil** or rock integrated over the **area** of the potential slip surface as well as any engineered structures put in place to increase slope stability. The primary effect of water within the slope is to reduce the normal stress acting across the potential slip surface, thereby reducing the shear strength along the surface. The driving force (or moment) is due primarily to the component of the slump block weight acting parallel to the potential slip surface, the weight of imprudently designed or constructed structures built on the slope, and seismic shaking. Movement can be triggered if the ratio of driving to resisting forces (or moments) is altered by adding water to the slope or by changing its geometry during construction projects.

See also Debris flow; Mass movement; Mass wasting

SMITH, WILLIAM (1769-1839)

English geologist and cartographer

William Smith is often called the founder of English **geology**, and the founder of stratigraphical geology. His interests in **fossils** and the countryside led to a method to identify **rock** strata, along with the first large-scale geological maps of any country. Smith contributed many practical innovations to the embryonic science of geology, and rose from humble beginnings to become a well known and respected scientific figure.

Smith was the eldest son of a village blacksmith, in Churchill, Oxfordshire. His father died when he was still young, and he was sent to live on his Uncle’s nearby farm. He attended the small local school, receiving a limited education, but his interest in mathematics was encouraged by friends and relatives, who gave him further tuition. Smith’s local reputation as an intelligent boy led him to become employed as an assistant to the surveyor Edward Webb. Webb initially employed Smith to take notes, hold the chain, and other trivial tasks, but was impressed enough to take the eighteen-year-old Smith into his home in Stow and give him an apprenticeship.

Surveying took Smith across much of England, and it was while in Somerset, just outside of Bath, that Smith began to formulate some key ideas. The **area** had many **coal** mines, and Smith was allowed to go into many to observe the rock strata. In 1795, he was employed by local landowners to survey a coal transportation canal, and this work offered Smith further observations of the local rocks. He had a keen interest in fossils, taking many samples in the course of his work. Smith began to speculate that there was a link between the types of fossils and the rock they were found in. He also began to make his first maps of the local rock structures.

After his work on the Bath canal was finished, in 1799, Smith traveled widely, performing a number of small engineering and surveying jobs, in which he observed much more of the English rock strata. While Smith discussed his ideas with many influential men, it was not until 1802 that his ideas began to be widely appreciated in the English scientific community. In that year he met Sir Joseph Banks, president of the Royal Society. Banks encouraged Smith to produce a book containing his ideas and maps. However, more than ten years were to pass before Smith produced any geological work. The pressures of work and some financial worries forced Smith to postpone and delay his writing.

In 1815, Smith, with the help of map engraver John Cary, finished his first of many geological maps, *A Delineation of the Strata of England and Wales, With part of Scotland*. Aside from being the first geological map of an entire country, it was also notable for the innovative use of colored contours to make differentiation clear. The map was well received, being exhibited to the Royal Institution, and Smith received an endowment from the Society for the Encouragement of the Arts, Manufacture and Commerce of fifty pounds.

A year later, over 250 copies of the map had been printed, and while they sold for the hefty price of five guineas (five and a quarter pounds) there were high printing costs. Smith found himself in grave financial difficulties at this time, mainly from a bad investment in a poor rock quarry, and was forced to sell his vast collection of fossils to the British Museum. He also encountered resistance to his rise in social status, in particular from the Geological Society of London president George Greenough. Greenough blocked Smith's membership, and produced a competing map which was cheaper.

Encouraged by his printer, Smith began to publish many more writings and smaller maps of the English counties, and finally he published a work on fossils, the four volume *Strata Identified by Organized Fossils* (1816–19). This presented Smith's observation that fossils of the same type always appeared in the same rock strata, and so could be used to identify the rocks. Smith also began to give lectures on his ideas in the North of England, where he was accompanied by his nephew John Phillips, who later became professor of Geology at Oxford University.

Smith began to suffer from arthritis, and became quite deaf, and was forced to give up lecturing. He became the land steward of Sir John Johnstone of Hackness, in Yorkshire. This gave him the opportunity to study the area in fine detail, and in 1832 he produced a map of the district to the scale of six and a half inches to the mile.

The Geological Society of London, under a new president, awarded Smith the first Wollaston Medal for his work in 1831, and he was given a number of other awards and degrees in recognition of his contributions to geology. He was also given a government pension, and finally achieved a degree of economic security, if somewhat late in life. He was selected as a member of the group to select the stone for the new Houses of Parliament, but once again he had bad luck with quarries, and the stone failed to withstand the detailed carvings of the ornately decorated buildings. However, Smith actually died before the final selection of stone was made, and his notes suggest he had some reservations about the quality of the stone.

Smith died in 1839, after catching a chill on his way to a meeting of the British Association in Birmingham. His work was mainly practical, and he stressed the commercial benefits that could be gained from his work. His mapping of strata enabled others to deduce areas of likely coal sources, and his many county maps remained in use for decades after his death. Some historians have commented that he was lucky that England has such 'well behaved' rock strata, as opposed to continental **Europe** where alpine folding made interpretation difficult. However, Smith should still be given credit for recognizing details others did not, and for making his ideas public.

See also Fossil record; Geologic map; Stratigraphy

SMOG

Smog refers to an atmospheric condition of atmospheric instability, poor visibility, and large concentrations of gaseous and particulate air pollutants. The word "smog" is an amalgam of the words "smoke" and "fog." There are two types of smog: reducing smog characterized by sulfur dioxide and particulates, and photochemical smog characterized by **ozone** and other oxidants.

Reducing smog refers to air pollution episodes characterized by high concentrations of sulfur dioxide and smoke (or particulate aerosols). Reducing smog is also sometimes called London-type smog, because of famous incidents that occurred in that city during the 1950s.

Reducing smogs first became common when industrialization and the associated burning of **coal** caused severe air pollution by sulfur dioxide and soot in European cities. This air pollution problem first became intense in the nineteenth century, when it was first observed to damage human health, buildings, and vegetation.

There have been a number of incidents of substantial increases in human illness and mortality caused by reducing smog, especially among higher-risk people with chronic respiratory or heart diseases. These toxic pollution events usually occurred during prolonged episodes of calm atmospheric conditions, which prevented the dispersion of emitted gases and particulates. These circumstances resulted in the accumulation of large atmospheric concentrations of sulfur dioxide and particulates, sometimes accompanied by a natural **fog**, which became blackened by soot. The term smog was originally coined as a label for these coincident occurrences of **atmospheric pollution** by sulfur dioxide and particulates.

Coal smoke, in particular, has been recognized as a pollution problem in England and elsewhere in **Europe** for centuries, since at least 1500. Dirty, pollution-laden fogs occurred especially often in London, where they were called "pea-soupers." The first convincing linkage of a substantial increase in human mortality and an event of air pollution was in Glasgow in 1909, when about 1,000 deaths were attributed to noxious smog during an episode of atmospheric stagnation. A North American example occurred in 1948 in Donora, Pennsylvania, an industrial town located in a valley near Pittsburgh. In that case, a persistent fog and stagnant air during a four-day period coupled with large emissions of sulfur dioxide and particulates from heavy industries to cause severe air pollution. A large increase in the rate of human mortality

Wildfires in Indonesia caused smog thick enough that these girls need to wear masks on their way to school. © *Michael S. Yamashita/Corbis. Reproduced by permission.*

was associated with this smog; 20 deaths were caused in a population of only 14,100. An additional 43% of the population was made ill in Donora, 10% severely so.

The most famous episode of reducing smog was the so-called "killer smog" that afflicted London in the early winter of 1952. In this case, an extensive atmospheric stability was accompanied by a natural, white fog. In London, these conditions transformed into a noxious "black fog" with almost zero visibility, as the concentrations of sulfur dioxide and particulates progressively built up. The most important sources of emissions of these pollutants were the use of coal for the generation of **electricity**, for other industrial purposes, and to heat homes because of the cold temperatures. In total, this smog caused 18 days of greater-than-usual mortality, and 3,900 deaths were attributed to the deadly episode, mostly of elderly or very young persons, and those with pre-existing respiratory or coronary diseases.

Smogs like the above were common in industrialized cities of Europe and **North America**, and they were mostly caused by the uncontrolled burning of coal. More recently, the implementation of clean-air policies in many countries has resulted in large improvements of air quality in cities, so that severe reducing smogs no longer occur there. Once the severe effects of reducing smogs on people, buildings, vegetation, and other resources and values became recognized, mitigative actions were developed and implemented.

However, there are still substantial problems with reducing smogs in rapidly industrializing regions of eastern Europe, the former Soviet Union, China, India, and elsewhere. In these places, the social priority is to achieve rapid economic growth, even if environmental quality is compromised. As a result, control of the emissions of pollutants is not very stringent, and reducing smogs are still a common problem.

To a large degree, oxidizing or Los Angeles-type smogs have supplanted reducing smog in importance in most industrialized countries. Oxidizing smogs are common in sunny places where there are large emissions of nitric oxide and **hydrocarbons** to the atmosphere, and where the atmospheric conditions are frequently stable. Oxidizing smogs form when those emitted (or primary) pollutants are transformed through photochemical reactions into secondary pollutants, the most important of which are the strong oxidant gases, ozone and peroxyacetyl nitrate. These secondary gases are the major components of oxidizing smog that are harmful to people and vegetation.

Typically, the concentrations of these various chemicals vary predictably during the day, depending on their rates of emission, the intensity of sunlight, and atmospheric stability. In the vicinity of Los Angeles, for example, ozone concentrations are largest in the early-to-mid afternoon, after which these gases are diluted by fresh air blowing inland from the Pacific Ocean. These winds blow the polluted smog further inland, where pine **forests** are affected on the windward slopes of nearby mountains. The light-driven photochemical reactions also cease at night. This sort of daily diurnal cycle is typical of places that experience oxidizing smog.

Humans are sensitive to ozone, which causes irritation and damage to membranes of the respiratory system and eyes, and induces asthma. People vary greatly in their sensitivity to ozone, but hypersensitive individuals can suffer considerable discomfort from exposure to oxidizing smog.

See also Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Biosphere; Ultraviolet rays and radiation

SNOW • *see* PRECIPITATION

SOIL AND SOIL HORIZONS

Soil is found in the top layers of **regolith**, the unconsolidated (uncompacted) matter comprised of soil, sediment, and portions of **bedrock** that form the outer crustal layer of the Earth's surface. Soil includes varying amounts of organic matter mainly derived from plants and animal decay.

Because soil is a superficial layer, it can be highly variable and has a composition that can be readily modified by **weather** (e.g., rainfall).

Soil is usually found in stratified layers (i.e. a layer of black soil over subsurface layers of **sand** and/or **clay**. Although different for each geographic **area**, geologists use a generic soil model from which to describe unique area differences.

A soil horizon is a coherent layer of soil—similar in characteristics such as composition, texture, and color—that define the horizon from other soil types. Geologists construct soil profiles of an area by describing the various soil horizons (horizontal layers) that exist within a vertical column of soil. Soil profiles, descriptive of the type and relation of soil horizons, are unique to different geologic and climatic areas.

The outermost (most superficial) soil horizon in a soil profile is termed the "A" horizon. Accordingly, "B," "C," and "D" horizons indicate successively deeper layers. A typical soil profile might then consist of vegetation (not strictly a part of the soil horizon), overlying an "A" horizon of humus (zone of leeching), overlying a "B" horizon of regolith (Zone of accumulation) that was superficial to a layer of bedrock.

The zone of leeching is so defined because **water** is able to percolate through the horizon.

Within the United States, in areas of the Eastern United States with a temperate, humid **climate** with adequate rainfall (generally defined as greater than 24 inches of rain per year) the soil profile typically consists of forest vegetation growing on the "A" horizon zone of leeching that consists of thick humus and sand. The underlying "B" horizon comprising the zone of accumulation is often clay that is rich in **iron** or **aluminum**. The "C" horizon is regolith and the "D" horizon is bedrock. A unique feature of this soil profile is that the mineral calcite ($CaCO_3$) often leeches out of the soil. The loss of this natural buffer allows the soil to become acidic.

In the Western United States—with a more arid climate—a much sparser layer of vegetation (an eventual contributor of organic material) covers an "A" zone of leeching horizon of thin humus and unaltered silicates. The "B" horizon (zone of accumulation) is composed of **caliche**. As with the Eastern profile the "C" and "D" horizons are regolith and bedrock. Caliche is rich in calcite because the calcium carbonate in the upper soil becomes briefly dissolved in the sparse rains that then wash the calcium carbonate down to the caliche layer.

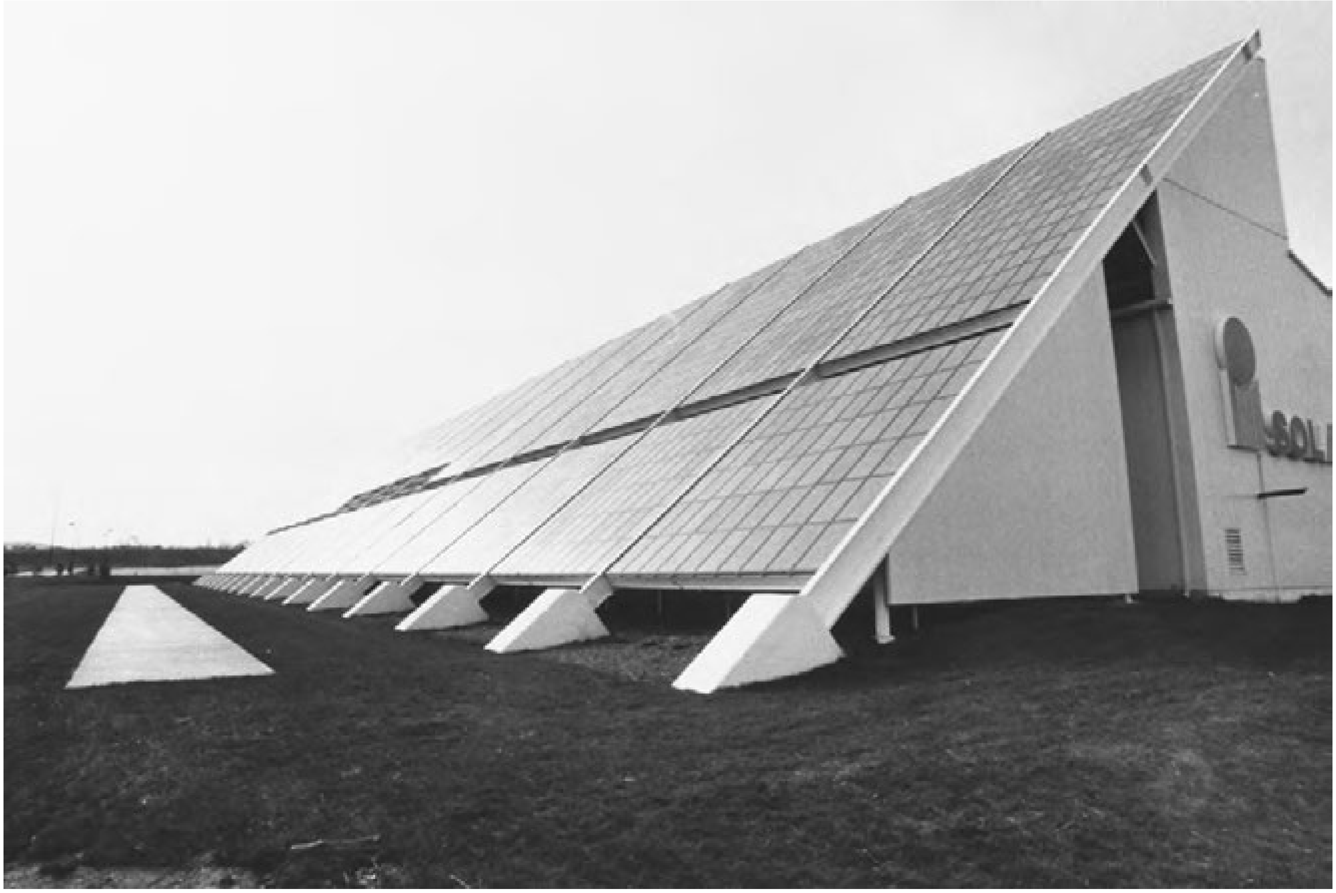
A tropical soil profile features lush vegetation overlying a "B" horizon layer of accumulation that is rich in bauxites and iron oxide. In the tropical soil profile, the "A" horizon may be missing or just a few centimeters thick. In this thin layer, there is a rapid turnover of organic decay and decomposition. All the **quartz** or clay elements are generally "weathered out" and the loss of calcite severe.

See also Leaching; Mass wasting; Porosity and permeability; Rate factors in geologic processes; Runoff; Sedimentation; Stratigraphy

SOLAR ENERGY

Earth's surface receives energy from processes in Earth's interior and from the **Sun**. Heat from the interior comes from radioactive elements in the mantle and core, tidal kneading by the **Moon** and Sun, and residual heat from the earth's formation. This interior heat is radiated through the surface at a global rate of 3×10^{13} watts (W)—about .07 W per square yard (.06 W/m^2). The Sun, in contrast, provides 1.73×10^{17} W, 5,700 times more power than Earth radiates from within and about 30,000 times more than is released by all human activity. **Clouds**, air, land, and sea absorb 69% of the energy arriving from the Sun and reflect the rest back into **space**. The ocean, which covers about 70% of the earth's surface, does about 70% of the absorbing of solar energy.

Between its absorption as heat and its final return to space as infrared radiation, solar energy takes many forms, including kinetic energy in flowing air and **water** or latent heat in evaporated water. Solar energy keeps the **oceans** and atmosphere from **freezing** and drives all winds and currents. A small fraction of Earth's solar energy income is intercepted by green plants, providing the flow of food energy that sustains most



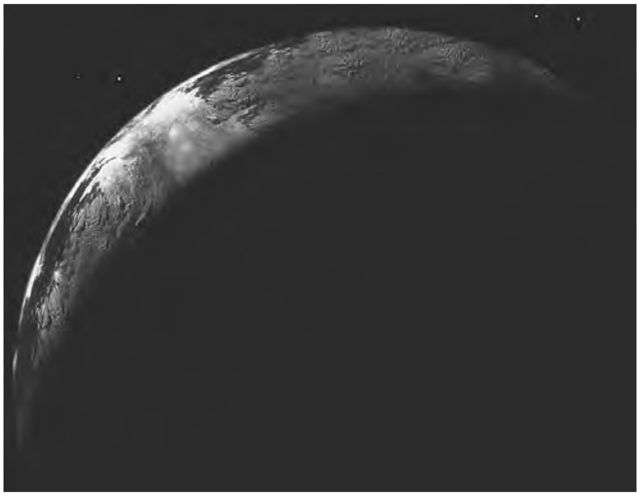
Solar energy is becoming a viable alternate source of power for many people. ***Library of Congress.***

earthly life. Only a few organisms, including thermophilic bacteria infiltrating the **crust** and organisms specialized to live in the vicinity of hydothermal deep-sea vents, derive their energy from Earth's interior rather than from the Sun.

Regional variations in solar input contribute to **weather** patterns and seasonal changes. On average Earth's surface is more nearly at a right angle to the Sun's rays near the equator, so the tropics absorb more solar energy than the higher latitudes. This creates an energy imbalance between the equator and the poles, an imbalance that the circulation of the atmosphere and oceans redress by transporting energy away from the equator. During each half of the year the daylight side of each hemisphere is tilted at a steeper angle to the sun than during the other half, and so intercepts less solar energy; this results in seasonal climatic changes.

Solar energy is also of technological importance. Utilization of the Sun as an energy source has been routine on spacecraft for decades and is becoming more frequent on the ground. Electromagnetic radiation from the Sun, unlike the major conventional power sources, produces no smokestack emissions, **greenhouse gases**, or radioactive wastes; and its production cannot be manipulated for profit or political leverage. On the down side, sunlight is a diffuse or spread-out energy source compared to any fuel and is directly available only during the day. Yet, even at high latitudes in **Europe** and **North America**, where most of the world's energy is consumed, the ground receives from the Sun a long-term average of 83.6 W per square yard (100 W/m^2). This average is inclusive of "dark" hours. Both indirect and direct harvesting of this energy income is possible. Indirect solar schemes, including **wind** power, wood heat, and the burning of alcohol, methane, or hydrogen, run on energy derived at second hand from sunlight. Direct schemes use sunlight as such to heat buildings or water, generate **electricity**, or supply high-temperature process heat to industrial systems.

Because conventional electricity generation is expensive and polluting, much effort has been devoted to solar electricity generation. Electricity can be generated from sunlight either thermally or photovoltaically. Thermal methods focus the Sun's rays on looped pipes through which molten salt, hot air, or steam flows. This hot fluid is then used either at first or second hand to run generators, much as heat from **coal** or nuclear fuel is used in conventional power plants. Photovoltaic electrical generation depends on flat, specially designed transistors (solar cells) that convert incident light to electricity. At 83.6 W/yard^2 (100 W/m^2) average solar input, 38 square yards (32 m^2) of 33% efficient solar cells—a square 18 feet (5.5 m) on a side—could supply 800 kilowatt-hours of electricity per



NASA photo of light/dark terminator from space. © *M. Agliolo. Reproduced by permission.*

month, the approximate usage of the average U.S. household. An efficiency of 32.3% has been demonstrated in the laboratory, but most commercial photovoltaic cells are only about 10% efficient. Unlike the unused heat from a ton of coal or uranium, however, the sunlight not converted to electricity by a solar cell entails neither monetary cost nor pollution, and so cannot be viewed as waste.

Despite its obvious advantages, photovoltaic electricity generation has long been limited to specialized off-grid applications by the high cost of solar cells. However, cell prices have fallen steadily, and several large-scale photovoltaic electricity projects are now under way in the U.S. and elsewhere.

See also Atmospheric circulation; Coronal ejections and magnetic storms; Energy transformations; Global warming; Insolation and total solar irradiation; Meteorology; Ocean circulation and currents; Seasonal winds; Solar illumination: Seasonal and diurnal patterns; Solar sunspot cycles; Sun; Ultraviolet rays and radiation

SOLAR ILLUMINATION: SEASONAL AND DIURNAL PATTERNS

Earth rotates about its **polar axis** as it revolves around the **Sun**. Earth's polar axis is tilted 23.5° to the orbital plane (ecliptic plane). Combinations of **rotation**, **revolution**, and tilt of the polar axis result in differential illumination and changing illumination patterns on Earth. These changing patterns of illumination result in differential heating of Earth's surface that, in turn, creates seasonal climatic and **weather** patterns.

Earth's rotation results in cycles of daylight and darkness. One daylight and night cycle constitutes a diurnal cycle. Daylight and darkness are separated by a terminator—a shadowy zone of twilight. Earth's rate of rotation—approximately 24 hours—fixes the time of the overall cycle (i.e., the length of a day). However, the number of hours of daylight and darkness within each day varies depending upon **latitude** and season (i.e., Earth's location in its elliptical orbital path about the Sun).

On Earth's surface, a circle of illumination describes a latitude that defines an extreme boundary of perpetual daylight or perpetual darkness. Tropics are latitudes that mark the farthest northward and farthest southward line of latitude where the solar zenith (the highest angle the Sun reaches in the sky during the day) corresponds to the local zenith (the point directly above the observer). At zenith, the Sun provides the most direct (most intense) illumination. Patterns of illumination and the apparent motion of the Sun on the hypothetical celestial sphere establish several key latitudes. The North Pole is located at 90° North latitude; the Arctic Circle defines an **area** from 66.5 N to the North Pole; the Tropic of Cancer defines an area from the Equator to 23.5 N; the Tropic of Capricorn defines an area from the equator to 23.5 S; the Antarctic Circle defines an area from 66.5 S to the South Pole.

There are seasonal differences in the amount and directness of daylight (e.g., the first day of summer always has the longest period of daylight, and the first day of winter the least amount of daylight). With regard to the Northern Hemisphere, at winter solstice (approximately December 21), Earth's North Pole is pointed away from the Sun, and sunlight falls more directly on the Southern Hemisphere. At the summer solstice (approximately June 21), Earth's North Pole is tilted toward the Sun, and sunlight falls more directly on the Northern Hemisphere. At the intervening vernal and autumnal equinoxes, both the North and South Pole are oriented so that they have the same angular relationship to the Sun and, therefore, receive equal illumination. In the Southern Hemisphere, the winter and summer solstices are exchanged so that the solstice that marks the first day of winter in the Northern Hemisphere marks the first day of summer in the Southern Hemisphere.

At autumnal equinox (approximately September 21), there is uniform illumination of Earth's surface (i.e., 12 hrs of daylight everywhere except exactly at the poles which are both illuminated). At winter solstice (approximately September 21), there is perpetual sunlight within the Antarctic Circle (i.e., the Antarctic circle is fully illuminated). At vernal equinox (approximately March 21), the illumination patterns return to the state of the autumnal equinox. At vernal equinox, there is uniform illumination of Earth's surface (i.e., 12 hrs of daylight everywhere except exactly at the poles which are both illuminated). At summer solstice (approximately June 21), there is perpetual sunlight within the Arctic Circle (i.e., the Arctic Circle is fully illuminated).

The illumination patterns in the polar regions—within the Artic Circle and Antarctic Circle—are dynamic and inverse. As the extent of perpetual illumination (perpetual daylight) increases—to the maximum extent specified by the latitude of each circle—the extent of perpetual darkness increases within the other polar circle. For example, at winter solstice, there is no illumination within the Artic circle (i.e., perpetual night within the area 66.5° N to the North Pole). Conversely, the Antarctic Circle experiences complete daylight (i.e., perpetual daylight within the area 66.5° S to the North Pole.). As Earth's axial tilt and revolution about the Sun continue to produce changes in polar axial orientation that result in a progression to the vernal equinox, the circle of perpetual darkness decreases in extent round the North Pole as the circle of perpetual daylight decreases around the South pole. At equinox, both polar regions receive the same illumination.

At the Equator, the Sun is directly overhead at local noon at both the vernal and autumnal equinox. The Tropic of Cancer and the Tropic of Capricorn denote latitudes where the Sun is directly overhead at local noon at a solstice. Along the Tropic of Cancer, the Sun is directly overhead at local noon at the June 21 solstice (the Northern Hemisphere's summer solstice and the Southern Hemisphere's winter solstice). Along the Tropic of Capricorn, the Sun is directly overhead at local noon at the December 21 solstice.

Precession of Earth's polar axis also results in a long-term precession of seasonal patterns.

Although the most dramatic changes in illumination occur within the polar regions, the differences in daylight hours—affecting the amount of **solar energy** or solar **insolation** received—cause the greatest climatic variations in the middle latitude temperate regions. The polar and equatorial regions exhibit seasonal patterns, but these are much more uniform (i.e., either consistently cold in the polar regions or consistently hot in the near equatorial tropical regions) than the wild **temperature** swings found in temperate climates.

Differences in illumination are a more powerful factor in determining climatic seasonal variations than Earth's distance from the Sun. Because Earth's orbit is only slightly elliptical, the variation from the closest approach at perihelion (approximately January 3) to the farthest Earth orbital position at aphelion six months later (varies less than 3%). Because the majority of tropospheric heating occurs via conduction of heat from the surface, differing amounts of sunlight (differential levels of solar insolation) result in differential temperatures in Earth's **troposphere** that then drive convective currents and establish low and high pressure areas of convergence and divergence.

See also Atmospheric composition and structure; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Revolution and rotation; Solar energy; Year, length of

SOLAR SUNSPOT CYCLE

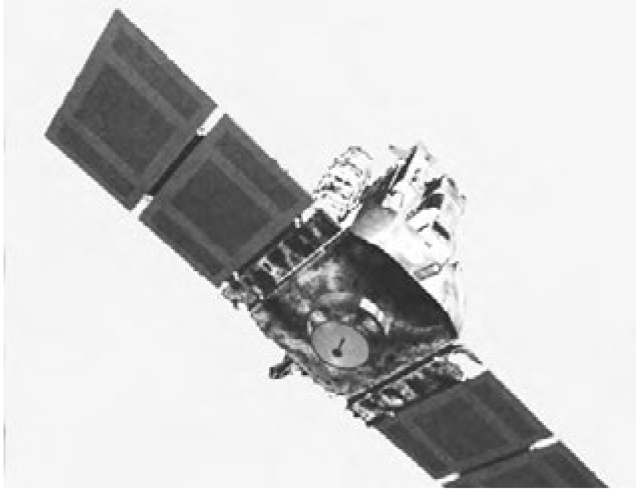
A sunspot is an **area** of the Sun's photosphere, appearing darker to the eye than surrounding areas of the **Sun**. Although very hot by any terrestrial standard, sunspot regions are cooler that surrounding solar surface. Sunspots occur in cycles and are associated with a strong solar **magnetic field**. Variations in the solar magnetic field impact the **space** environment of Earth (sometime termed "space weather" and therefore have at least a correlated effect on Earth's **weather** and climatic conditions.

Large sunspots, visible to the naked eye, were noted by the ancient Chinese. The first specific mention of sunspots in modern scientific literature was by Italian astronomer and physicist **Galileo Galilei** (1564–1642) in his *Starry Messenger* published in 1610. Sunspot occurrence has been carefully noted by astronomers ever since. Astronomers have found that the frequency of sunspots varies with a period of between 11 and 13 years. This corresponds to the period of solar activity cycle involving solar flares, prominences and other phenomena associated with the outer layers of the Sun.

At the beginning of the solar cycle a few sunspots appear at the higher latitudes on the Sun near the poles. The sunspots then appear to move across the face of the Sun due to its **rotation**. Large spots may last for several rotation periods of about a month in length. As the cycle progresses the number of spots increases and they tend to be formed at lower latitudes toward the equator. The end of the cycle is marked by a marked drop in the number of low-latitude sunspots, which is followed immediately by the beginning of the next cycle, as small numbers of spots begin to appear at high latitudes.

Astronomers now know that sunspots are essentially **magnetic storms** on the surface of the Sun. The spots usually occur in pairs. Just as a bar-magnet placed under a sheet of paper will show a characteristic looping magnetic field when **iron** filings are scattered over the paper, so the sunspots making up the pair appear to be connected by a similar field. The ends of the bar magnet are characterized as being north or south magnetic poles depending on how a magnetic compass is affected by the poles. Similarly, each of the members of a sunspot pair will have the characteristics of either a north or south magnetic pole. During a particular cycle, the leading spot of the pair will always have the same polarity for spots formed in a particular hemisphere. The order of polarity is reversed for sunspot-pairs formed in the opposite hemisphere. Thus, if spots-pairs formed in the northern hemisphere of the Sun have the **lead** spot behaving as a south magnetic pole, the leading spot of a pair formed in the southern hemisphere will have north magnetic pole. This order of polar progression for the leading and trailing spots is preserved throughout the entire 11–13 year cycle. However, during the following sunspot cycle the order will be reversed in both hemispheres. This has led most astronomers to feel that the proper sunspot cycle should be reckoned as consisting of two 11–13 year cycles, since two cycles must pass before conditions are duplicated and the full pattern can repeat.

Although there have been attempts to link the solar cycle to changes on Earth, most are still characterized as correlations (i.e., the events are associated but there is no established cause and effect relationship. An exception may lie in the earth's weather. There have been some strongly suggestive correlations between solar activity and global **temperature** as well as rainfall variations. Analysis of tree-ring data spanning many centuries clearly shows the presence of a 11–13 year cycle. There is even compelling evidence from ancient **rock** layers that the solar cycle has been present since **Precambrian** times. Those involved in the launching and maintenance of Earth satellites are acutely aware that the upper layers of the earth's atmosphere respond to solar activity by expanding thereby increasing the atmospheric drag on satellites in low Earth orbit. Finally, there is a curious period of about 75 years shortly after Galileo's discovery when few sunspots were observed. This era is called the Maunder Minimum after the astronomer who first noted its existence. Other phenomena such as the **Aurora Borealis** (Northern Lights) that are associated with solar activity are also missing



The SOHO spacecraft gives astronomers a stationary view of the Sun. ***U.S. National Aeronautics and Space Administration (NASA).***

from European records during this period. The interval is also associated with a time of unusually severe winters in both **Europe** and **North America** and is often called the "little **ice** age." In this century, Jack Eddy has found evidence that there may have been similar periods of cold associated with earlier interruptions of the solar cycle. Unfortunately, our understanding of the solar cycle is sufficiently crude that we have no explanation of what might cause these interruptions. Indeed, our understanding of the basis for the cycle itself is still largely in a phenomenological phase.

The very strong magnetic fields (i.e. several thousand times the general field of the earth) in a sunspot account for the dark appearance of the spot. The hot atmosphere of the Sun contains a significant number of atoms having a net positive charge resulting from collisions between them (i.e., they are ionized, having lost one or more electrons). Charged particles may move along magnetic field lines, but not across them. Thus, a magnetic field exerts a kind of pressure on the gas and helps to support it against the gravitational force of the Sun itself. This force is usually balanced only by the pressure of the hot gas surrounding a sunspot. With part of the pressure being supplied by the magnetic field, the gas will cool to a lower temperature. Because it is not as hot, it appears dark compared to the bright surrounding region called the photosphere. While they appear dark by comparison, sunspots are still hotter than any blast furnace on the earth and are only dark by contrast with the brilliant solar surface. A close inspection of a sunspot shows it to have a dark central region called an umbra surrounded by a lighter radial structured region called a penumbra. These regions can be understood in terms of the spreading and weakening magnetic field emanating from the core of the sunspot.

In the second half of this century, Eugene Parker suggested a mechanism that accounts for much of the descriptive behavior of sunspots. The Sun does not rotate as a rigid body and the polar regions rotate somewhat more slowly than the equator. Because of the charged nature of the solar material, the Sun's general magnetic field is dragged along with the solar rotation. However, it will be dragged faster and further at the equator than at the rotational poles. Although the general field of the Sun is quite weak (i.e., similar to that of the earth), the differential rotation strengthens and distorts the field over time. One can imagine the faster-rotating regions of the equator dragging the local magnetic field so that the field lines are drawn out into long thin tubes. The more these tubes are stretched, the stronger the field becomes. The magnetic pressure exerted on the surrounding gas causes the material within the tube to become "buoyant" compared to the surrounding material and rise toward the surface. As the magnetic tube breaks the surface of the Sun, it forms two spot-like cross-sections where it clears the lower solar atmosphere. As the field direction is out of the solar surface at one spot and into it at the other, one of these spots will appear to have one kind of magnetic pole and the other spot will appear to have the other. The global nature of the general solar field will guarantee that the stretched magnetic tubes will yield leading spots with opposite polarities in opposite hemispheres. A reversal of the Sun's general field between 11–13 year cycles would account for the reversal of this order. However, there is no compelling explanation of why the general field should reverse after each 11–13 year solar cycle

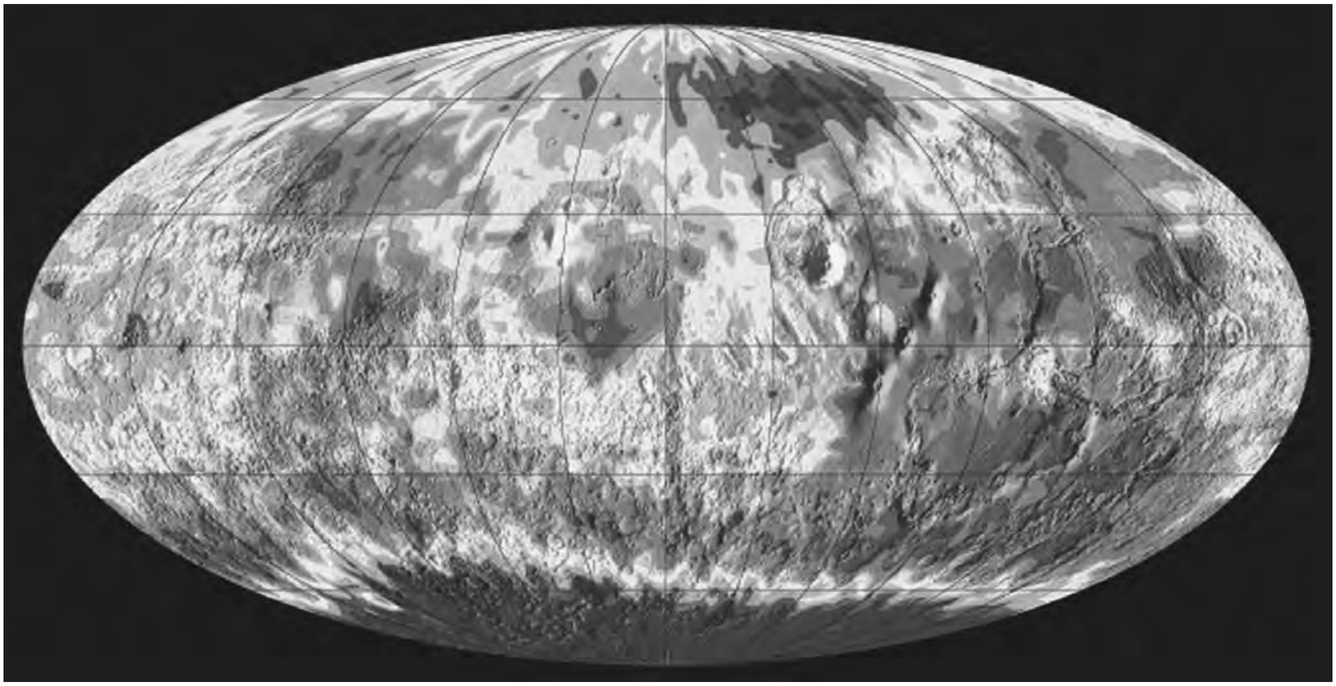
See also Aurora Borealis and Aurora Australialis; Coronal ejections and magnetic storms; Electricity and magnetism

SOLAR SYSTEM

Earth's solar system is comprised of the **Sun**, nine major planets, some 100,000 **asteroids** larger than 0.6 mi (1 km) in diameter, and perhaps 1 trillion cometary nuclei. While the major planets lie within 40 Astronomical Units (AU)—the average distance of Earth to the Sun—the outermost boundary of the solar system stretches to 1 million AU, one-third the way to the nearest star. Cosmologists and Astronomers assert that the solar system was formed through the collapse of a spinning cloud of interstellar gas and dust.

The central object in the solar system is the Sun. It is the largest and most massive object in the solar system; its diameter is 109 times that of Earth, and it is 333,000 times more massive. The extent of the solar system is determined by the gravitational attraction of the Sun. Indeed, the boundary of the solar system is defined as the surface within which the gravitational pull of the Sun dominates over that of the galaxy. Under this definition, the solar system extends outwards from the Sun to a distance of about 100,000 AU. The solar system is much larger, therefore, than the distance to the remotest known planet, Pluto, which orbits the Sun at a mean distance of 39.44 AU.

The Sun and the solar system are situated some 26,000 light years from the center of our galaxy. The Sun takes about 240 million years to complete one orbit about the galactic cen-



Map of Mars made by NASA's 2001 Mars *Odyssey* spacecraft. *AP/Wide World. Reproduced by permission.*

ter. Since its formation the Sun has completed about 19 such trips. As it orbits about the center of the galaxy, the Sun also moves in an oscillatory fashion above and below the galactic plane with a period of about 30 million years. During their periodic sojourns above and below the plane of the galaxy, the Sun and solar system suffer gravitational encounters with other stars and giant molecular **clouds**. These close encounters result in the loss of objects (essentially dormant cometary nuclei located in the outer Oort cloud) that are on, or near, the boundary of the solar system. These encounters also nudge some cometary nuclei toward the inner solar system where they may be observed as long-period **comets**.

The objects within our solar system demonstrate several essential dynamical characteristics. When viewed from above the Sun's North Pole, all of the planets orbit the Sun along near-circular orbits in a counterclockwise manner. The Sun also rotates in a counterclockwise direction. With respect to the Sun, therefore, the planets have prograde orbits. The major planets, asteroids, and short-period comets all move along orbits only slightly inclined to one another. For this reason, when viewed from Earth, the asteroids and planets all appear to move in the narrow zodiacal band of constellations. All of the major planets, with three exceptions, spin on their central axes in the same direction that they orbit the Sun. That is, the planets mostly spin in a prograde motion. The planets Venus, Uranus, and Pluto are the three exceptions, having retrograde (backwards) spins.

The distances at which the planets orbit the Sun increase geometrically, and it appears that each planet is roughly 64% further from the Sun than its nearest inner neighbor. The separation between successive planets increases dramatically beyond the orbit of Mars. While the inner, or terrestrial planets are typically separated by distances of about four-tenths of an AU, the outer, or Jovian planets are typically separated by 5—10 AU.

Although the asteroids and short-period comets satisfy, in a general sense, the same dynamical constraints as the major planets, we have to remember that such objects have undergone significant orbital **evolution** since the solar system formed. The asteroids, for example, have undergone many mutual collisions and fragmentation events, and the cometary nuclei have suffered from numerous gravitational perturbations from the planets. Long-period comets in particular have suffered considerable dynamical evolution, first to become members of the Oort cloud, and second to become comets visible in the inner solar system.

The compositional make-up of the various solar system bodies offers several important clues about the conditions under which they formed. The four interior planets—Mercury, Venus, Earth, and Mars—are classified as terrestrial and are composed of rocky material surrounding an iron-nickel metallic core. In contrast, Jupiter, Saturn, Neptune, and Uranus are classified as the "gas giants" and are large masses of hydrogen in gaseous, liquid, and solid form surrounding Earth-size **rock** and metal cores. Pluto fits neither of these categories, having an icy surface of frozen methane. Pluto more greatly resembles the satellites of the gas giants, which contain large fractions of icy material. This observation suggests that the initial conditions under which such ices might have formed only prevailed beyond the orbit of Jupiter.

In summary, any proposed theory for the formation of the solar system must explain both the dynamical and chemical properties of the objects in the solar system. It must also be sufficient flexibility to allow for distinctive features such as retrograde spin, and the chaotic migration of cometary orbits.

Astronomers almost universally assert that the best descriptive model for the formation of the solar system is the solar nebula hypothesis. The essential idea behind the solar nebula model is that the Sun and planets formed through the collapse of a rotating cloud of interstellar gas and dust. In this way, planet formation is postulated to be a natural consequence of star formation.

The solar nebula hypothesis is not a new scientific proposal. Indeed, the German philosopher Immanuel Kant first discussed the idea in 1755. Later, the French mathematician, Pierre Simon de Laplace (1749–1827) developed the model in his text, *The System of the World,* published in 1796.

The key postulate in the solar nebula hypothesis is that once a rotating interstellar gas cloud has commenced gravitational collapse, then the conservation of angular momentum will force the cloud to develop a massive, central **condensation** that is surrounded by a less massive flattened ring, or disk of material. The nebula hypothesis asserts that the Sun forms from the central condensation, and that the planets accumulate from the material in the disk. The solar nebula model naturally explains why the Sun is the most massive object in the solar system, and why the planets rotate about the Sun in the same sense, along nearly circular orbits and in essentially the same plane.

During the gravitational collapse of an interstellar cloud, the central regions become heated through the release of gravitational energy. This means that the young solar nebular is hot, and that the gas and (vaporized) dust in the central regions is well mixed. By constructing models to follow the gradual cooling of the solar nebula, scientists have been able to establish a chemical condensation sequence. Near to the central proto-sun, the nebular **temperature** will be very high, and consequently no solid matter can exist. Everything is in a gaseous form. Farther away from the central proto-sun, however, the temperature of the nebula falls off. At distances beyond 0.2 AU from the proto-sun, the temperature drops below 3,100°F (1,700°C). At this temperature, **metals** and oxides can begin to form. Still further out (at about 0.5 AU), the temperature will drop below 1,300°F (730°C), and silicate rocks can begin to form. Beyond about 5 AU from the proto-sun, the temperature of the nebula will be below –100°F (–73°C), and ices can start to condense. The temperature and distance controlled sequence of chemical condensation in the solar nebula correctly predicts the basic chemical make-up of the planets.

Perhaps the most important issue to be resolved in future versions of the solar nebula model is that of the distribution of angular momentum. The problem for the solar nebula theory is that it predicts that most of the mass and angular momentum should be in the Sun. In other words, the Sun should spin much more rapidly than it does. A mechanism is therefore required to transport angular momentum away from the central proto-sun and redistribute it in the outer planetary disk. One proposed transport mechanism invokes the presence of a **magnetic field** in the nebula, while another mechanism proposed the existence of viscous stresses produced by turbulence in the nebular gas.

Precise dating of meteorites and lunar rock samples indicate that the solar system is 4.6 to 5.1 billion years old. The meteorites also indicate an age spread of about 20 million years, during which time the planets themselves formed.

The standard solar nebula model suggests that the planets were created through a multi-step process. The first important step is the coagulation and **sedimentation** of rock and **ice** grains in the mid-plain of the nebula. These grains and aggregates, 0.4 in (1 cm) to 3 ft (1 m) in size, continue to accumulate in the mid-plain of the nebula to produce a swarm of some 10 trillion larger bodies, called planetesimals, that are some 0.6 mi (1 km), or so in size. Finally, the planetesimals themselves accumulate into larger, self-gravitating bodies called proto-planets. The proto-planets were probably a few hundred kilometers in size. Finally, growth of proto-planet-sized objects results in the planets.

The final stages of planetary formation were decidedly violent—it is probable that a collision with a Mars-sized proto-planet produced Earth's **Moon**. Likewise, it is thought that the retrograde rotations of Venus and Uranus may have been caused by glancing proto-planetary impacts. The rocky and icy planetesimals not incorporated into the proto-planets now orbit the Sun as asteroids and cometary nuclei. The cometary nuclei that formed in the outer solar nebula were mostly ejected from the nebula by gravitational encounters with the large Jovian gas giants and now reside in the Oort cloud.

One problem that has still to be worked-out under the solar nebula hypothesis concerns the formation of Jupiter. The estimated accumulation time for Jupiter is about 100 million years, but it is now known that the solar nebula itself probably only survived for 100,000 to 10 million years. In other words, the accumulation process in the standard nebula model is too slow by at least a factor of 10 and maybe 100.

Of great importance to the study of solar systems was the discovery in 1999 of an entire solar system around another star. Although such systems should be plentiful and common in the cosmos, this was the first observation of another solar system. Forty-four light-years from Earth, three large planets were found circling the star Upsilon Andromedae. Astronomers suspect the planets are similar to Jupiter and Saturn—huge spheres of gas without a solid surface.

See also Astronomy; Big Bang theory; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Cosmology; Dating methods; Earth (planet); Earth, interior structure; Geologic time; Revolution and rotation

SOLID SOLUTION SERIES

A solid solution series is the compositional range between end-member **minerals** that share the same basic chemical formula but experience substitution of elements in one or more atomic sites. This substitution occurs when an element in a mineral formula can be replaced by another of similar size and charge to make a new mineral. For example, **iron** and magnesium can readily replace one another in a mineral. In some cases, the substitution can be complete and range from entirely one element to another element, resulting in end-member mineral compositions. One example is **olivine**, which can vary from Mg_2SiO_4 (forsterite) to Fe_2SiO_4 (fayalite). This is known as complete solid solution. Such a mineral can also consist of any intermediate percentage of either end-member. The compositional range between end-member minerals that exhibit complete solid solution is known as a solid solution series.

Another example of a complete solid solution series is between siderite $FeCO_3$ and rhodochrosite, $MnCO_3$. In this and the olivine example, the cation is replaced. Complete anion substitution series are less common, but one example is given by KCl to KBr. Solid solutions can be more chemically complicated as well, with more than one element being replaced. In **plagioclase**, a complete series exists between albite, $NaAlSi_3O_8$ and anorthite, $CaAl_2Si_2O_8$. In this case, Na^+ is similar enough in size to substitute for Ca^{2+}. Because the charges are different, a shift in the number of **aluminum** and **silicon** atoms is required to maintain neutrality.

Complete solid solution is also possible with three end-members. In the pyroxenes for example, compositional variation among of Ca^{2+}, Mg^{2+}, or Fe^{2+} is often represented in terms of three simplified components: wollastonite ($CaSiO_3$), enstatite ($MgSiO_3$), and ferrosilite ($FeSiO_3$).

The actual compositional variation of a given mineral that forms a solid solution series may be expressed by the abbreviated mineral names with its proportion subscripted. An olivine that has been analyzed and determined to consist of 25% Mg^{2+} and 75% Fe^{2+} would be represented by $Fo_{25}Fa_{75}$. This composition may also be written in terms of the molecular formula: $(Mg_{0.25}Fe_{0.75})SiO_4$. Graphical forms are also common. In the case of two end-members, a bar diagram is used and the composition is plotted on the bar. When three end-members are present, a diagram that places each end-member at the point of an equilateral triangle allows compositional variations to be plotted anywhere within the triangle.

See also Chemical elements; Feldspar

SOLOMON, SUSAN (1956-)

American atmospheric chemist

Susan Solomon played a key role in discovering the cause of a major threat to the earth—the loss of the protective ozone layer in the upper atmosphere. **Ozone** protects all life on Earth from large amounts of damaging ultraviolet radiation from the **sun**. Solomon, an atmospheric chemist, was first to propose the theory explaining how chlorofluorocarbons, gases used in refrigerators and to power aerosol spray cans, could in some places on the globe lead to ozone destruction in the presence of stratospheric **clouds**.

Solomon said in an interview with Lee Katterman that she recalls "exactly what got me first interested in science. It was the airing of Jacques Cousteau on American TV when I was nine or ten years old." Solomon said that as a child she was very interested in watching natural history programming on television. This sparked an interest in science, particularly biology. "But I learned that biology was not very quantitative," said Solomon in the interview. By the time she entered the Illinois Institute of Technology, Solomon met her need for quantitative study by choosing **chemistry** as her major at the Illinois Institute of Technology. A project during Solomon's senior year turned her attention toward **atmospheric chemistry**. The project called for measuring the reaction of ethylene and hydroxyl radical, a process that occurs in the atmosphere of Jupiter. As a result of this work, Solomon did some extra reading about planetary atmospheres, which led her to focus on atmospheric chemistry.

During the summer of 1977, just before entering graduate school at University of California at Berkeley, Solomon worked at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. She met research scientist Paul Crutzen at NCAR, who introduced her to the study of ozone in the upper atmosphere. In the fall at Berkeley, Solomon sought out Harold Johnston, a chemistry professor who did pioneering work on the effects of the supersonic transport (SST) on the atmosphere. Solomon credits Crutzen and Johnston for encouraging her interest in atmospheric chemistry. After completing her course work toward a Ph.D. in chemistry at Berkeley, Solomon moved to NCAR to do her thesis research with Crutzen.

She received a Ph.D. in chemistry in 1981 and then accepted a research position at the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Laboratory in Boulder, Colorado. Initially, Solomon's research focused on developing computer models of ozone in the upper atmosphere. Ozone is a highly reactive molecule composed of three atoms of **oxygen**. By comparison, the oxygen that is essential to the metabolism of living things is a relatively stable combination of two oxygen atoms. In the upper atmosphere between about 32,000 and 100,000 feet altitude, a layer of ozone exists that absorbs much of the sun's deadly ultraviolet radiation, thereby protecting all life on Earth.

In 1985, scientists first reported that, during the months of spring in the Southern Hemisphere (September and October), the density of the ozone layer over **Antarctica** had been decreasing rapidly in recent years. The cause of this hole in the ozone layer was unknown and many scientists began to look for its cause. In 1986, the scientific community wanted to send some equipment to Antarctica to measure atmospheric levels of ozone and nitrogen dioxide. Much to the surprise of her scientific colleagues, Solomon volunteered to travel to Antarctica to get the needed measurements; until then, she had concentrated on theoretical studies, but the chance to understand the cause of the ozone hole prompted Solomon to take up experimental work. Solomon led an expedition to Antarctica during August, September, and October of 1986, where she and co-workers measured the amounts of several atmospheric components, including the amount of chlorine dioxide in the upper atmosphere. The level of this atmospheric chemical was much higher than expected and provided an important clue in determining why the ozone hole had appeared. Back at her NOAA lab in Boulder, Solomon wrote a research article that provided a theoretical explanation for the ozone hole. Solomon showed how the high level of chlorine dioxide was consistent with fast chemical destruction of ozone triggered by reactions occurring on stratospheric clouds. The extra chlorine dioxide was derived from chlorofluorocarbons released into the atmosphere from sources such as foams and leaking refrigeration equipment. Solomon returned to Antarctica for more measurements in August of 1987. Her explanation for the cause of the ozone hole is now generally accepted by scientists, and has led many countries of the world to curtail the production and use of chlorofluorocarbons.

Solomon's scientific studies to uncover the likely cause of the ozone hole have led to public recognition and many awards. In 1989, Solomon received the gold medal for exceptional service from the U.S. Department of Commerce (the agency that oversees the NOAA) She has testified several times before congressional committees about ozone depletion and is increasingly sought out as an expert on ozone science and policy (although the latter role is one she does not welcome, Solomon admitted in her interview, since she considers herself a scientist and not a policy expert).

Solomon was born on January 19, 1956, in Chicago, Illinois. Her father, Leonard Solomon, was an insurance agent. Susan's mother, Alice Rutman Solomon, was a fourth-grade teacher in the Chicago public schools. Solomon continues to study the atmospheric chemistry of ozone and has added Arctic ozone levels to her research subjects.

See also Chloroflurocarbon (CFC); Global warming; Greenhouse gases and greenhouse effect; Ozone layer and hole dynamics; Ozone layer depletion

SOROSILICATES

The most abundant rock-forming **minerals** in the **crust** of the earth are the silicates. They are formed primarily of **silicon** and **oxygen**, together with various **metals**. The fundamental unit of these minerals is the silicon-oxygen tetrahedron. These tetrahedra have a pyramidal shape, with a relatively small silicon cation (Si^{+4}) in the center and four larger oxygen anions (O^{-2}) at the corners, producing a net charge of –4. **Aluminum** cations (Al^{+3}) may substitute for silicon, and various anions such as hydroxyl (OH^{-}) or fluorine (F^{-}) may substitute for oxygen. In order to form stable minerals, the charges that exist between tetrahedra must be neutralized. This can be accomplished by the sharing of oxygen atoms between tetrahedra, or by the binding together of adjacent tetrahedra by various metal cations. This in turn creates characteristic silicate structures that can be used to classify silicate minerals into **cyclosilicates**, **inosilicates**, **nesosilicates**, **phyllosilicates**, sorosilicates, and **tectosilicates**.

Minerals formed by two silicon-oxygen tetrahedra sharing oxygen atoms are called sorosilcates. These double tetrahedra contain two silicon cations and seven oxygen anions, giving them a net charge of –6. Various metal cations neutralize the charges between double tetrahedra. Most of the minerals in the sorosilicate group are rare, and many are found in metamorphic rocks. Examples of sorosilicates that form during **metamorphism**, as well as during the crystallization of **igneous rocks**, include those in the epidote group. Epidote has the formula $Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$, and epidote group minerals are comprised of both single and double silicon-oxygen tetrahedra. Another sorosilicate mineral is hemimorphite ($Zn_4(Si_2O_7)(OH)_2{\cdot}H2O$). Hemimorphite is a secondary mineral (meaning that it is an alteration product), found in the oxidized portions of zinc ore deposits.

See also Chemical bonds and physical properties

SOUND TRANSMISSION

Sound waves are pressure waves that travel through Earth's **crust**, **water** bodies, and atmosphere. Natural sound frequencies specify the frequency attributes of sound waves that will efficiently induce vibration in a body (e.g., the tympanic membrane of the ear) or that naturally result from the vibration of that body.

Sound waves are created by a disturbance that then propagates through a medium (e.g., crust, water, air). Individual particles are not transmitted with the wave, but the propagation of the wave causes particles (e.g., individual air molecules) to oscillate about an equilibrium position.

Every object has a unique natural frequency of vibration. Vibration can be induced by the direct forcible disturbance of an object or by the forcible disturbance of the medium in contact with an object (e.g. the surrounding air or water). Once excited, all such vibrators (i.e., vibratory bodies) become generators of sound waves. For example, when a **rock** falls, the surrounding air and impacted crust undergo sinusoidal oscillations and generate a sound wave.

Vibratory bodies can also absorb sound waves. Vibrating bodies can, however, efficiently vibrate only at certain frequencies called the natural frequencies of oscillation. In the case of a tuning fork, if a traveling sinusoidal sound wave has the same frequency as the sound wave naturally produced by the oscillations of the tuning fork, the traveling pressure wave can induce vibration of the tuning fork at that particular frequency.

Mechanical resonance occurs with the application of a periodic force at the same frequency as the natural vibration frequency. Accordingly, as the pressure fluctuations in a resonant traveling sound wave strike the prongs of the fork, the prongs experience successive forces at appropriate intervals to produce sound generation at the natural vibrational or natural sound frequency. If the resonant traveling wave continues to exert force, the amplitude of oscillation of the tuning fork will increase and the sound wave emanating from the tuning fork will grow stronger. If the frequencies are within the range of human hearing, the sound will seem to grow louder. Singers are able to break **glass** by loudly singing a note at the natural vibrational frequency of the glass. Vibrations induced in the glass can become so strong that the glass exceeds its elastic limit and breaks. Similar phenomena occur in rock formations.

Whales can communicate over vast distances by calling out to each other underwater. Water, which is denser than air, can transmit sound waves many times further than air. ***AP/Wide World. Reproduced by permission.***

All objects have a natural frequency or set of frequencies at which they vibrate.

Sound waves can potentiate or cancel in accord with the principle of **superposition** and whether they are in phase or out of phase with each other. Waves of all forms can undergo constructive or destructive interference. Sound waves also exhibit Doppler shifts—an apparent change in frequency due to relative motion between the source of sound emission and the receiving point. When sound waves move toward an observer the Doppler effect shifts observed frequencies higher. When sound waves move away from an observer the Doppler effect shifted observed frequencies lower. The Doppler effect is commonly and easily observed in the passage of planes, trains, and automobiles.

The speed of propagation of a sound wave is dependent upon the density of the medium of transmission. **Weather** conditions (e.g., **temperature**, pressure, **humidity**, etc.) and certain geophysical and topographical features (e.g., mountains or hills) can obstruct sound transmission. The alteration of sound waves by commonly encountered meteorological conditions is generally negligible except when the sound waves propagate over long distances or emanate from a high frequency source. In the extreme cases, atmospheric conditions can bend or alter sound wave transmission.

The speed of sound through a fluid—inclusive in this definition of "fluid" are atmospheric gases—depends upon the temperature and density of the fluid. Sound waves travel faster at higher temperature and density of medium. As a result, in a standard atmosphere, the speed of sound (reflected in the Mach number) lowers with increasing altitude.

Meteorological conditions that create layers of air at dramatically different temperatures can refract sound waves.

The speed of sound in water is approximately four times faster than the speed of sound in air. SONAR sounding of ocean terrain is a common tool of oceanographers. Properties such as pressure, temperature, and salinity also affect the speed of sound in water.

Because sound travels so well under water, many marine biologists argue that the introduction of man-made noise (e.g., engine noise, propeller cavitation, etc) into the **oceans** within the last two centuries interferes with previously evolutionarily well-adapted methods of sound communication between marine animals. For example, man-made noise has been demonstrated to interfere with long-range communications of whales. Although the long term implications of this interference are not fully understood, many marine biologists fear that this interference could impact whale mating and lead to further population reductions or extinction.

See also Aerodynamics; Atmospheric composition and structure; Atmospheric inversion layers; Electromagnetic spectrum; Energy transformations; Seismograph; Seismology

SOUTH AMERICA

The South American continent stretches from about 10° above the equator to almost 60° below it, encompassing an **area** of 6,880,706 sq mi (17,821,028 sq km). This is almost 12% of the surface area of the earth. It is about 3,180 mi (5,100 km) wide at its widest point, and is divided into 10 countries. The continent can be divided into three main regions with distinct environmental and geological qualities: the highlands and plateaus of the east, which are the oldest geological feature in the continent; the Andes Mountains, which line the west coast and were created by the subduction of the Nazca plate beneath the continent; and the riverplain, between the highlands, which contains the Amazon River. The South American **climate** varies greatly based on the distance from the equator and the altitude of the area, but the range of temperatures seldom reaches 36°F (20°C), except in small areas.

The Eastern highlands and plateaus are the oldest geological region of South America, and are thought to have bordered on the African continent at one time, before the motion of the earth's **crust** and continental drift separated the continents. The Eastern highlands can be divided into three main sections, the Guiana Highlands, the Brazilian Highlands, and the Patagonian Highlands. The Guiana Highlands are found in the Guianan states, south Venezuela, and northeastern Brazil. Their highest peak, Roraima, reaches a height of 9,220 ft (2,810 m). This is a moist region with many waterfalls; it is in this range, in Venezuela, that the highest waterfall in the world, Angel Falls, is found. Angel Falls plummets freely for 2,630 ft (802 m).

The Brazilian Highlands make up more than one half of the area of Brazil, and range in altitude between 1,000 and 5,000 ft (305–1524 m). The highest mountain range of this region is called Serra da Mantiqueira, and its highest peak, Pico da Bandeira, is 9,396 ft (2,864 m) above sea level.

The Patagonian Highlands are in the south, in Argentina. The highest peak reaches an altitude of 9,462 ft (2,884 m), and is called Sierra de Cordoba.

The great mountain range of South America is the Andes Mountains, which extends more than 5,500 mi (8,900 km) all the way down the western coast of the continent. The highest peak of the Andes, called Mount Aconcagua, is on the western side of central Argentina, and is 22,828 ft (6,958 m) high. The Andes were formed by the motion of the earth's crust and its different tectonic plates. Some of them are continental plates, which are at a greater altitude than the other type of plate, the oceanic plates. All of these plates are in motion relative to each other, and the places where they border each other are regions of instability where various geological structures are formed, and where earthquakes and volcanic activity is frequent. The western coast of South America is a **subduction zone**, which means that the oceanic plate, called the Nazca plate, is being forced beneath the adjacent continental plate. The Andes Mountains were thrust upwards by this motion, and can still be considered "under construction" by the earth's crust. In addition to the Nazca plate, the South American and Antarctic plates converge on the west coast in an area called the Chile Triple Junction, at about 46° south **latitude**. The complexity of **plate tectonics** in this region sparks interest for geologists.

The geological instability of the region makes earthquakes common all along the western region of the continent, particularly along the southern half of Peru.

The Andes are dotted with volcanoes; some of the highest peaks in the mountain range are volcanic in origin, many of which rise above 20,000 ft (6,100 m). There are three major areas in which volcanoes are concentrated. The first of these appears between latitude 6° north and 2° south, straddles Colombia and Ecuador, and contains active volcanoes. The second, and largest region, lies between latitudes 15° and 27° south; it is about 1,240 mi (2,000 km) long and 62–124 mi (100–200 km) wide, and borders Peru, Bolivia, Chile, and Argentina. This is the largest concentration of volcanoes in the world, and the highest volcanoes in the world are found here. The volcanic activity, however, is low and it is generally geysers that erupt here. The third region of volcanic concentration is also the most active. It lies in the central valley of Chile, mostly between 33° and 44° south.

The climate in the Andes varies greatly, depending on both altitude and latitude, from hot regions, to Alpine meadow regions, to the **glaciers** of the South. The snowline is highest in southern Peru and northern Chile, at latitude 15–20° south, where it seldom descends below 19,000 ft (5,800 m). This is much higher than at the equator, where the snowline descends to 15,000 ft (4,600 m). This vagary is attributed to the extremely dry climate of the lower latitude. In the far south of the continent, in the region known as Tierra del Fuego, the snowline reaches as low as 2,000 ft (600 m) above sea level.

The Andes are a rich source of mineral deposits, particularly copper, silver, and gold. In Venezuela, they are mined for copper, **lead**, **petroleum**, phosphates, and salt; diamonds are found along the Rio Caroni. Columbia has the richest deposits of **coal**, and is the largest producer of gold and platinum in South America. Columbia is also wealthy in emeralds, containing the largest deposits in the world with the exception of Russia. In Chile, the Andes are mined largely for their great copper stores in addition to lead, zinc, and silver. Bolivia has enormous tin mines. The Andes are also a source of tungsten, antimony, nickel, chromium, cobalt, and sulfur.

The Amazon basin is the largest river basin found in the world, covering an area of about 2.73 million sq mi (7 million sq km). The second largest river basin, which is the basin of the River Zaire in the African Congo, is less than half as large. The **water** resources of the area are spectacular; the volume of water that flows from the basin into the sea is about 11% of all the water drained from the continents of the earth. The greatest flow occurs in July, and the least is in November. While there are many **rivers** flowing through the basin, the most important and well known of these is the Amazon. The width of the Amazon ranges from about 1 mi (1.6 km) to as wide as 5–6 mi (5–6 km), and although it is usually only about 20–40 ft (6–12 m) deep, there are narrow channels where it can reach a depth of 300 ft (100 m).

The Amazon basin was once an enormous bay, before the Andes were pushed up along the coasts. As the mountain range grew, they held back the ocean and eventually the bay became an inland sea. This sea was finally filled by the **erosion** of the higher land surrounding it, and finally a huge plain, crisscrossed by countless waterways, was created. Most of this region is still at sea level, and is covered by lush jungle and extensive wetlands. This jungle region contains the largest extant rain forest in the world. Despite the profusion of life that abounds here, the **soil** is not very rich; the fertile regions are those which receive a fresh layer of river silt when the Amazon **floods**, which occurs almost every year.

The climate of South America varies widely over a large range of altitudes and latitudes, but only in isolated regions is the **temperature** range greater than about 36°F (20°C). The coldest part of the continent is in the extreme southern tip, in the area called Tierra del Fuego; in the coldest month of the year, which is July, it is as cold as 32°F (0°C) there. The highest temperature of the continent is reached in a small area of northern Argentina, and is about 108°F (42°C). However, less than 15 days a year are this warm, and the average temperature in the same area for the hottest month of the year, which is January, is about 84°F (29°C).

Colombia borders Venezuela, Brazil, Ecuador, and Peru, and encompasses an area of 440,831 sq mi (1,141,748 sq km). It is found where Panama of Central America meets the South American continent, and its location gives it the interesting feature of having coastal regions bordering on both the Atlantic and the Pacific **oceans**. It is a country of diverse environments, including coastal, mountain, jungle, and island regions, but in general can be considered to consist of two major areas based on altitude: the Andes mountains and the lowlands.

The Andes in Colombia can be divided into three distinct ranges, which run approximately from north to south in parallel ridges. The Cordillera Occidental, or westernmost range, attains a maximum altitude of about 10,000 ft (3,000 m). The Cordillera Oriental, which is the eastern range, is much higher, and many of its peaks are covered with snow all year round. Its highest peak is about 18,000 ft (5,490 m) high, and it has many waterfalls, such as the Rio Bogota, which falls 400 ft (120 m). The Cordillera Central, as its name implies, runs between the Occidental and Oriental Cordilleras. It contains many active volcanoes as well as the highest peak in Colombia, Pico Cristobal Colon, which is 19,000 ft (5,775 m) high.

The lowlands of the east cover two thirds of Colombia's land area. It is part of the Orinoco and Amazon basins, and thus is well watered and fertile. Part of this region is covered with rich equatorial rain forest. The northern lowlands of the coastal region also contain several rivers, and the main river of Colombia, the Magdalena, begins there.

Venezuela covers an area of 352,144 sq mi (912,0250 sq km). It is the most northern country of South America, and can be divided up into four major regions. The Guiana Highlands in the southeast make up almost half of Venezuela's land area, and are bordered by Brazil and Guyana. It is here that the famous Angel Falls, the highest waterfall in the world, is found. The Northern Highlands, which are a part of the Andes Mountains, contain the highest peak in Venezuela—Pico Bolivar, which reaches a height of 16,427 ft (5,007 m). This range borders on much of the coastal region of Venezuela, and despite its proximity to both the Caribbean and the equator, it has many peaks that are snow-covered year-round. The Maracaibo basin, one-third of which is covered by Lake Maracaibo, is found in the northwest. It is connected to the Caribbean Sea, and although it contains fresh water at one end of the lake, as it nears the ocean it becomes more saline. Not surprisingly, most of the basin consists of wetlands. The Llanos de Orinoco, which borders on Colombia in the southwestern part of Venezuela, is watered by the Orinoco River and its tributaries. The Orinoco has a yearly discharge almost twice as large as that of the Mississippi, and from June to October, during the rainy season, many parts of the Llanos are inaccessible due to flooding.

Ecuador received its name from the fact that it straddles the equator. Its area is 103,930 sq mi (269,178 sq km), making it the smallest of the Andean countries. Its eastern and western lowlands regions are divided by the Andes Mountains, which run through the center of the country. This part of the Andes contains an active **volcano** region; the world's highest active volcano, Cotopaxi, which reaches an altitude of 19,347 ft (5,897 m), is found here. The western lowlands on the coast contain a tropical rain forest in the north, but become extremely dry in the south. The eastern lowlands are part of the Amazon basin, and are largely covered by tropical rainforest. The rivers Putumayo, Napo, and Pastaza flow through this area.

Ecuador also claims the famous Galapagos Islands, which lie about 650 mi (1,040 km) off the coast. These 12 islands are all volcanic in origin, and several of the volcanoes are still active. The islands are the home of many species unique to the world, including perhaps the most well-known of their numbers, the Galapagos tortoise.

Peru covers an area of 496,225 sq. mi (1,285,216 sq. km), making it the largest of the Andean countries. Like Ecuador, it is split by the Andes Mountains into two distinct sections. The eastern coastal region is mostly covered with mountains, and in many places, the ocean borders on steep cliffs. In the northern part, however, there is a relatively flat region that is suitable for agriculture. In the east, the lowlands are mostly covered by the thick tropical rain forest of the Amazon basin. The southern part of the Andes in Peru contain many volcanoes, some of which are still active, and Lake Titicaca, which is shared by Bolivia. Lake Titicaca is remarkable for, among the large **lakes** with no ocean outlet, Titicaca is the highest in the world. It is 125 mi (200 km) at its largest length and 69 mi (110 km) at its largest breadth, which is not quite half as large as Lake Ontario; but it lies at an altitude of 12,507 ft (3,812 m) above sea level.

Bolivia has an area of 424,164 sq mi (1,098,581 sq km), and is the only landlocked country in South America besides Paraguay. The western part of the country, which borders on

Ecuador and Chile, is covered by the Andes Mountains, and like most of this part of the Andes, it contains many active volcanoes. In the southern part of the range, the land becomes more arid, and in many places salt marshes are found. Among these is Lake Poopo, which lies 12,120 ft (3,690 m) above sea level. This saline lake is only 10 ft (3 m) deep. In the northern part of the range, the land becomes more habitable, and it is here that Lake Titicaca, which is shared with Peru, is found.

The eastern lowlands of Bolivia are divided into two distinct regions. In the north, the fertile Llanos de Mamore is well watered and is thickly covered with vegetation. The southeastern section, called the Gran Chaco, is a semiarid savanna region.

Chile is the longest, narrowest country in the world; although it is 2,650 mi (4,270 km) long, it is only about 250 mi (400 km) wide at its greatest width. It encompasses an area of 284,520 sq mi (736,905 sq km). The Andes divides into two branches along the eastern and western edges of the country. The eastern branch contains the highest of the Andean peaks, Aconcagua, which is 20,000 ft (6,960 m), and the highest point on the continent. The Andes in Chile has the greatest concentration of volcanoes on the continent, containing over 2,000 active and dormant volcanoes, and the area is plagued by earthquakes.

In the western coastal region of north and central Chile, the land meets the ocean in a long line of cliffs which reach about 8,800 ft (2,700 m) in altitude. The southern section of this coastal mountain range moves offshore, forming a group of about 3,000 islands extending in a line all the way to Cape Horn, which is the southernmost point on the continent. The coast in this area is quite remarkable in appearance, having numerous **fjords**. There are many volcanic islands off the coast of Chile, including the famous Easter Island, which contains some unusual archeological remains.

The southern part of the coastal region of Chile is a temperate area, but in the north it contains the Atacama **Desert**, which is the longest and driest desert in the world. Iquique, Chile, which lies in this region, is reported to have at one time suffered 14 years without any rain at all. The dryness of the area is thought to be due to a sudden temperature inversion as **clouds** move from the cold waters off the shore and encounter the warmth of the continent; this prevents water from precipitating from the clouds when they reach the shoreline. It has been suggested also that the sudden rise of the Andes Mountains on the coast contributes to this effect.

Argentina, the second largest of the South American countries, covers an area of 1,073,399 sq mi (2,780,092 sq km). The Andes Mountains divide western Argentina from Chile, and in the south, known as Tierra de Fuego, this range is still partly covered with glaciers.

A large part of Argentina is a region of lowlands and plains. The northern part of the lowlands, called the Chaco, is the hottest region in Argentina. In the northwestern part of Argentina near the Paraguayan and Brazilian borders, are found the remarkable Iguassa Falls. They are 2.5 mi (4 km) wide and 269 ft (82 m) high. As a comparison, Niagara Falls is only 5,249 ft (1,599 m) wide and 150–164 ft (46–50 m) high. The greatest part of the lowland plains is called the Pampa, which is humid in the east and semiarid in the west.

The southern highlands of Patagonia, which begins below the Colorado River, is a dry and mostly uninhabited region of plateaus. In the Tierra del Fuego the southernmost extension of the Andes is found. They are mostly glaciated, and many glacial lakes are found here. Where the mountains descend into the sea, the glaciers have shaped them so that the coast has a fjord-like appearance.

The Falkland Islands lie off the eastern coast of Argentina. They are a group of about 200 islands consisting of rolling hills and peat valleys, although there are a few low mountains north of the main islands. The sea around the Falkland Islands is quite shallow, and for this reason they are thought to lie on an extension of the **continental shelf**.

Paraguay, which has an area of 157,048 sq mi (406,752 sq km), is completely landlocked. About half of the country is part of the Gran Chaco, a large plain west of the Paraguay River, which also extends into Bolivia and Argentina. The Gran Chaco is swampy in places, but for the most part consists of scrubland with a few isolated patches of forest. East of the Paraguay River, there is another plain which is covered by forest and seasonal marshes. This region becomes a country of flat plateaus in the easternmost part of Paraguay, most of which are covered with evergreen and deciduous **forests**.

Uruguay, which is 68,037 sq mi (176,215 sq km) in area, is a country bounded by water. To the east it borders the Atlantic Ocean, and there are many lagoons and great expanses of **dunes** found along the coast. In the west, Uruguay is bordered by the river Uruguay, and in the south by the La Plata **estuary**. Most of the country consists of low hills with some forested areas.

With an area of 3,286,487 sq mi (8,511,965 sq km), Brazil is by far the largest country in South America, taking up almost half of the land area of the continent. It can be divided into two major geographical regions: the highlands, which include the Guiana Highlands in the far north and the Brazilian Highlands in the center and southeast, and the Amazon basin.

The highlands mostly have the appearance of flat tablelands, which are cut by deep rifts, and clefts that drain them; these steep river valleys are often inaccessible. In some places, the highlands have been shaped by erosion so that their surfaces are rounded and hill-like, or even give the appearance of mountain peaks. Along the coast, the plateaus plummet steeply to the ocean to form great cliffs, which can be as high as 7,000–8,000 ft (2,100–2,400 m). Except for the far north of Brazil, there are no coastal plains.

The lowlands of Brazil are in the vast Amazon basin, which is mostly covered with dense tropical rain forest, the largest tract of unbroken rainforest in the world. The many rivers and tributaries that water the region create large marshes in places. The Amazon is home to many indigenous peoples and as yet uncounted species of animals and plants found nowhere else in the world.

French Guiana encompasses an area of 35,900 sq mi (93,000 sq km), and is found north of Brazil. The area furthest inland is a region of flat plateaus that becomes rolling hills in the central region of the country, while the eastern coastal area is a broad plain consisting mostly of poorly drained marshland. Most of the country is covered with dense tropical rain forest, and the coast is lined with mangrove swamps. French Guiana possesses a few island territories as well; the most famous of these, Devil's Island, was the former site of a French penal colony.

North of French Guiana lies Suriname, another tiny coastal country that has an area of 63,251 sq mi (163,820 sq km). The southern part of the country is part of the Guiana Highlands, and consists of very flat plateaus cut across by great rifts and steep gullies. These are covered with thick tropical rain forest. North of the highlands is an area of rolling hills and deep valleys formed by rivers and covered with forest. The extreme north of Suriname lies along the coast and is a flat swamp. Several miles of mangrove swamps lie between this region and the coast.

East of Suriname is the country of Guyana, with a land area of 83,000 sq mi (215,00 sq km). The Guiana Highlands are in the western and southern parts of Guyana. As with Suriname and French Guiana, these are cut up deeply by steep and sudden river valleys, and covered with dense rain forest. The western part of the Guiana Highlands are called the Pakaraima Mountains, and are much higher than the other plateaus in Guyana, reaching an altitude of as much as 9,220 ft (2,810 m). The highlands become a vast area of rolling hills in the central part of Guyana due to the effects of erosion; this sort of terrain takes up more than two thirds of the country. In the north along the coast is a swampy region as in Suriname and French Guiana, with many lagoons and mangrove swamps.

See also Continental drift theory; Delta; Depositional environments; Desert and desertification; Earth (planet); Forests and deforestation; Orogeny; Rapids and waterfalls; Rivers; Seasonal winds; Volcanic eruptions

SOUTH POLE • *see* GEOGRAPHIC AND MAGNETIC POLES

SOUTHERN LIGHTS • *see* AURORA BOREALIS AND AURORA AUSTRALIALIS

SPACE

Space is the three-dimensional extension in which all things exist and move. Intuitively, it feels that we live in an unchanging space. In this space, the height of a tree or the length of a table is exactly the same for everybody. Einstein's special theory of relativity explains that this intuitive feeling is really an illusion. Neither space nor time is the same for two people moving relative to each other. Only a combination of space and time, called space-time, is unchanged for everyone. Einstein's general theory of relativity states that the force of **gravity** is a result of a warping of this space-time by heavy objects, such as planets. According to the **Big Bang theory** of the origin of the universe, the expansion of the universe began from infinitely curved space-time. Scientists still do not know whether this expansion will continue indefinitely, or whether the universe will collapse again in a Big Crunch. Meanwhile, astronomers are continually learning about outer space from terrestrial and orbiting telescopes, space probes sent to other planets in the **solar system**, and other scientific observations. This is just the beginning of the exploration of the unimaginably vast void, beyond Earth's outer atmosphere, in which a journey to the nearest star would take 3,000 years traveling at a million miles per hour.

The difference in the perception of space and time, predicted by the special theory of relativity, can be observed only at very high velocities close to that of light. A man driving past at 50 mph (80 kph) will appear only a hundred million millionths of an inch thinner as you stand watching on the sidewalk. By themselves, three-dimensional space and one-dimensional time are different for different people. Taken together, however, they form a four-dimensional space-time in which distances are the same for all observers. We can understand this idea by using a two-dimensional analogy. Suppose that a man's definition of south and east is not the same as a woman's. The woman travels from city A to city B by going 10 miles along her south and then 5 miles along the man's east. The man travels from A to B by going 2 miles along his south and 11 miles along the woman's east. Both, however, move exactly the same distance of 11.2 miles south-east from city A to B. In the same way, if we think of space as south and time as east, space-time is something like south-east.

The general theory of relativity states that gravity is the result of the curving of this four-dimensional space-time by objects with large mass. A flat stretched rubber membrane will sag if a heavy **iron** ball is placed on it. If you now place another ball on the membrane, the second ball will roll towards the first. This can be interpreted in two ways: as a consequence of the curvature of the membrane, or as the result of an attractive force exerted by the first ball on the second one. Similarly, the curvature of space-time is another way of interpreting the attraction of gravity. An extremely massive object can curve space-time around so much that not even light can escape from its attractive force. Such objects, called black holes, probably exist in the universe. Astronomers believe that the disk found in 1994 by the Hubble **telescope**, at the center of the elliptical galaxy M87 near the center of the Virgo cluster, is material falling into a supermassive black hole estimated to have a mass three billion times the mass of the **Sun**.

The relativity of space and time and the curvature of space-time do not affect our daily lives. The high velocities and huge concentrations of matter, needed to manifest the effects of relativity, are found only in outer space on the scale of planets, stars, and galaxies. Our own Milky Way galaxy is a mere speck, 100,000 light years across, in a universe that spans ten billion light years. Though astronomers have studied this outer space with telescopes for hundreds of years, the modern space age began only in 1957 when the Soviet Union put the first artificial **satellite**, *Sputnik 1*, into orbit around the earth. At present, there are hundreds of satellites in orbit gathering information from distant stars, free of the distorting effect of the earth's atmosphere. Even though no manned

Earth rising. ***U.S. National Aeronautics and Space Administration (NASA).***

spacecraft has landed on other worlds since the Apollo **Moon** landings, several space probes, such as the *Voyager 2* and the *Magellan,* have sent back photographs and information from the Moon and from other planets in the solar system. There are many questions to be answered and much to be achieved in the exploration of space. The Hubble telescope, repaired in space in 1993 and 2002, has sent back data that has raised new questions about the age, origin, and nature of the universe. The launch of a United States astronaut to the Russian *Mir* space station in March 1995, the docking of the United States **space shuttle** *Atlantis* with *Mir*, and the **international space station** currently under construction have opened up exciting possibilities for space exploration.

See also Astronomy; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; History of manned space exploration; Physics; Relativity theory; Solar system; Space and planetary geology; Space physiology

SPACE PHYSIOLOGY

Space physiology is concerned with the structure and functioning of the body under the conditions encountered by space travelers. To date, these conditions have been confined to the environment of the spacecraft that houses the astronauts. In the future, however, as travel to other bodies in the **solar system** is undertaken, space physiology will include the atmospheric and gravitational conditions found on these planets, moons, or other stellar bodies.

Aside from the lunar missions of the 1960s, man’s extraterrestrial voyages have been confined to orbital forays aboard space capsules or space stations. But even orbiting around Earth poses difficulties for the astronauts. The reduced **gravity** of a spacecraft makes it difficult for the body to distinguish “up” from “down.” On Earth, such distinction by the vestibular organ of the inner ear is easy, because of the orienting power of gravity. In the **space shuttle** and the developing **international space station**, all writing on the walls is oriented in the same direction, to provide the brain with a reference point.

Low gravity (also known as microgravity) affects other body systems besides the vestibular system. The propioceptive system—the system of nerves in the joints and muscles that tell us where the arms and legs are without any visual inspection—can also be affected. Low gravity reduces or eliminates the tensions impinging on the joints and muscles, which can make the appendages appear invisible to the brain.

Such confusion between what the eye sees and the brain perceives can result in what has been termed space sickness. This is somewhat analogous to the feeling of nausea experienced by someone trying to read in a moving car. The inner ear detects the motion of the car, or the spacecraft, but the eyes staring at the page of the book or the space outside the spacecraft do not detect motion. Space sickness is usually transient, and astronauts acclimate soon after going into orbit.

Microgravity also affects the skeletal structure of astronauts. The absence of stress-bearing activity and the loss of components of the bones, particularly calcium, have produced shortening and weakening of bones (essentially the development of osteoporosis) and the atrophy (wasting away) of muscles in astronauts who have been orbiting the earth for just several months. Even the heart becomes smaller. So far these conditions have reversed upon return to Earth. The extended missions of the future will need to incorporate more Earth-like gravitation conditions, or an exercise regimen, or both.

Space flight also affects the cardiovascular system of astronauts. The weakened muscles and bones cannot support the maintenance of the same rate of flow of blood as on Earth. Also, the diminished downward pull of gravity affects the ability of the body to pump blood to extremities like the legs. Fluid flow to the upper regions of the body is not affected, however. As a result, faces of astronauts often appear puffy. In a very real sense, astronauts become out of shape—so much so that Russian cosmonauts who spend months in orbit around the earth are sometimes carried away from the spacecraft on a stretcher upon return.

A physiological parameter that will become important when manned travel to other parts of the solar system begins is exposure to higher levels of radiation that will be encountered on planets where atmospheric constituents do not absorb the harmful energies. Genetic material can be damaged by high-energy (ionizing) cosmic radiation and high-energy particles, with adverse effects on the functioning of the body. Thus far, the relatively short-term voyages into space have not proven to be harmful. But the hazards posed by extended voyages of years or even decades are as yet unknown.

See also History of manned space exploration

SPACE AND PLANETARY GEOLOGY

Space and planetary **geology** comprises that branch of the discipline of geology that applies basic scientific principles to the study of the origin, development, and characteristics of **solar system** objects such as planets, satellites, **asteroids**, **comets**, meteorites, and interplanetary dust particles. On Earth, space and planetary geology investigations are generally limited to impact craters and impact effects upon Earth, and to the study of Earth as an analogue for other planets and their processes. As technology progresses in the future, the field of space and planetary geology will likely expand to include extra-solar system objects as well. Space and planetary geology is also called astrogeology.

Astronauts sleeping in freefall. Experiencing weightlessness over prolonged periods of time can produce detrimental physiological effects. *U.S. National Aeronautics and Space Administration (NASA).*

Space and planetary geology has it origins in telescopic observations of planets, satellites, and comets and in the study of meteorites. Telescopic maps of the **Moon** date from early work *c.* 1612 by **Galileo Galilei** (1564–1642). The first true lunar **geologic map** was that of Michael van Langren (1598–1675), which he completed in 1645. After this, many other such telescopic maps were made of the Moon over the next three centuries. During the period 1880 to 1925, several telescopic maps of topographic and geological features of Mercury and Mars were produced. The most famous of these were maps by Percival Lowell (1855–1916), which showed his interpreted “canals” on Mars. Meteoritics, which is the study of meteorites and their origins, traces its origin as a science back to the German physicist Ernst Florens Chladni (1756–1827). Chladni proposed convincing (but highly debated) arguments (*c.* 1794) that stones and masses of **iron** that were seen falling from the sky were in fact objects from space that produced fireballs as the fell through Earth’s atmosphere. That small objects (asteroids) were orbiting the **Sun** was confirmed shortly thereafter (1801–1807) by a group of Italian astronomers dubbed the “celestial police,” who discovered the first four known asteroids, Ceres, Pallas, Juno, and Vesta.

Mars rover, *Sojourner*, on the Martian surface. ***© Agence France Presse/Corbis-Bettmann. Reproduced by permission.***

Space and planetary geology received an essential boost with the advent of rocketry and space flight. Beginning with missions to the Moon in the late 1950s and early 1960s (i.e., *Luna* 2 and 3 in 1959 and *Ranger* 7 in 1964), detailed orbital photographs of the near side and far side of the Moon were obtained. From these photographs, the first detailed geological maps of the Moon were made, thus establishing a new **area** of planetary photo-geologic mapping. During the 1960s, spacecraft made other missions to Mars and Venus. *Mariner* 4 (1964) and *Mariner* 6 (1969) took the first detailed photographs of Mars, and *Mariner* 2 (1964) landed on Venus and recorded surficial conditions. In the late 1960s and early 1970s, spacecraft returned samples from the Moon (*Apollo* 11, 12, 14–17 and *Luna* 16, 17, 20, 21), thus ushering in a new era of geological sample studies of the Moon. Study of these samples allowed radiometric dating and careful chemical and physical analysis that led to the first comprehensive description of the geological history of the Moon. In the 1970s and 1980s, spacecraft made radar maps of Venus (*Venera* 15 and 16), imaged the outer planets and some of their satellites (*Voyager* 1 and 2), imaged and landed upon Mars (*Viking* 1 and 2), and imaged part of Mercury (*Mariner* 10). These data further expanded planetary geological mapping. In the 1980s and 1990s, spacecraft photographed Halley's comet (*Vega* 1 and 2, *Giotto*), made detailed radar maps of Venus (*Magellan*), imaged asteroids Gaspara and Ida (*Galileo*, NEAR), imaged and landed on Mars (*Mars Pathfinder*), and imaged Jupiter and its satellites (*Galileo*). With each new photographic set, geological mapping of planet and **satellite** surfaces was expanded. More spacecraft observations are planned or are underway for Mercury, Mars, Saturn, the Moon, and various asteroids and comets in the near future.

Imagery from the various rocky planets and satellites has led to detailed topographic and geologic mapping of all the imaged bodies, and such maps, published mainly by the U.S. Geological Survey, are available to the public. Relative age relationships among geologic units on the planetary surfaces, deduced from photographic imagery, has led to development of preliminary geological time scales for Mercury, Venus, the Moon, and Mars. Similar studies are underway for the large Jovian satellites (Callisto, Ganymede, and Europa), the Saturnian satellites (Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus), the Uranian satellites (Ariel, Umbriel, Titania, Miranda, and Oberon), and the Neptunian satellite, Triton.

The International Astronomical Union (IAU) is in charge of standardized nomenclature for planetary surface features and geological units. There are approximately forty IAU-approved, generic feature terms in use in planetary nomenclature. For example, a ridge on a planetary surface is a dorsum (plural = dorsa) and a chain of craters is a catena. A distinctive area of broken terrain is a chaos. The IAU has approved certain themes for assigning names to generic features on planets, satellites, and asteroids. For example, all craters on Venus shall be named for famous women and all dorsa for sky goddesses. Also, for example, on Mars all large craters are named for deceased scientists who have contributed to the study of Mars, all small craters are named for villages of the earth, all large valleys are named for Mars in various languages, and all small valleys are named for Earth's classical or modern **rivers**. On Jupiter's satellite, Europa, all craters are named for Celtic gods and heroes. There is a comprehensive, IAU-approved list of such themes and all new suggested names must be approved for use on maps by an IAU Task Group specific to the planetary body at issue.

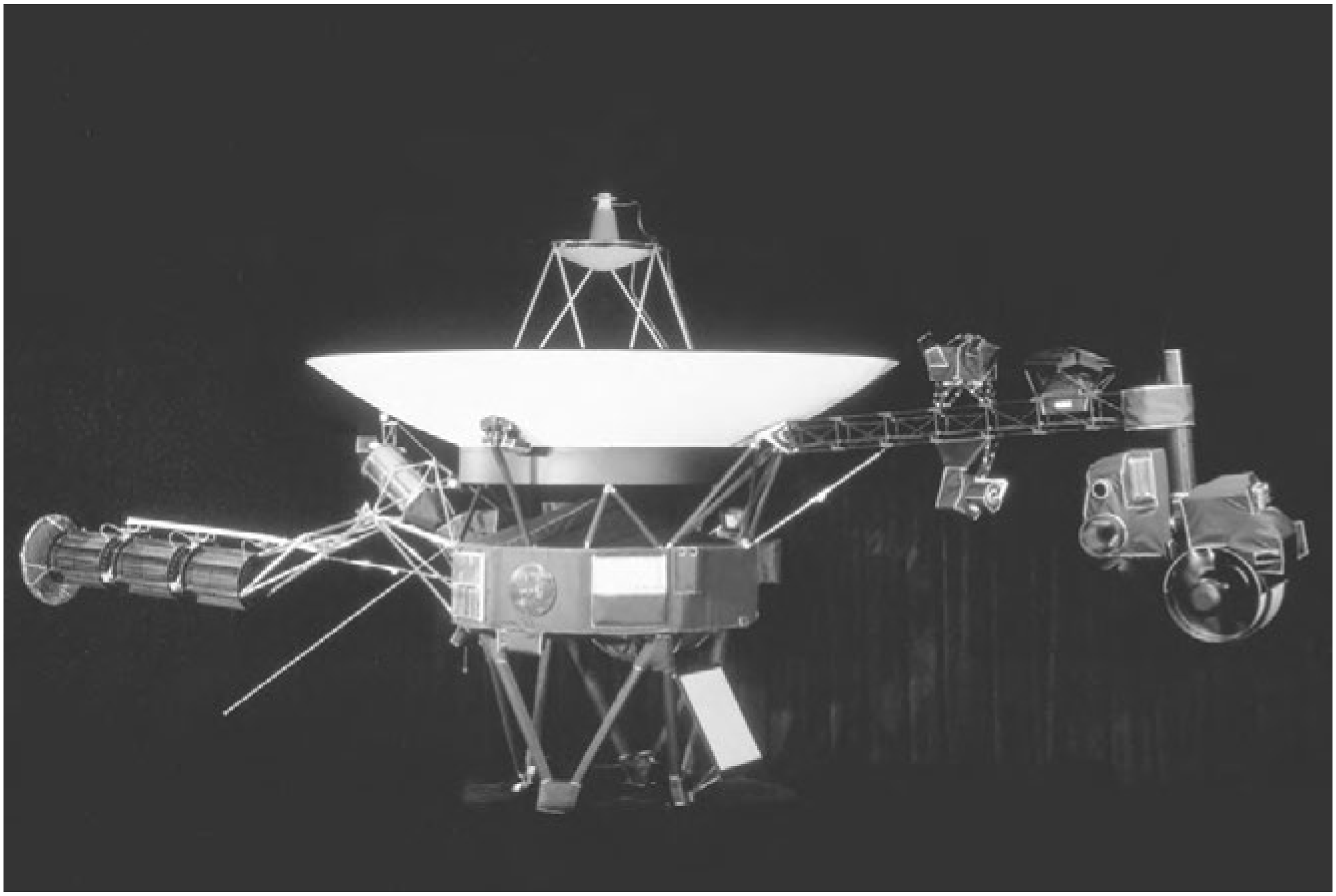
See also Astronomy; History of manned space exploration; Meteoroids and meteorites; Space probe

SPACE PROBE

A **space** probe is any unmanned instrumented spacecraft designed to carry out physical studies of space environment. As distinguished from satellites orbiting Earth under the influence of gravitational attraction, a space probe is rocketed into space with sufficient speed to achieve escape velocity (the velocity needed to obtain parabolic or hyperbolic orbit) and to reach a trajectory aimed at a pre-selected target.

The first recorded mention of a possibility of an unmanned probe dates back to 1919, when American physicist R. H. Goddard (1882–1945) suggested a series of space based experiments. However, in large part to Goddard's advancements in rocketry, it took only 33 years for the concept of space experiment to reappear. In 1952, the term "space probe" was introduced by E. Burgess and C. A. Cross in a short paper presented to the British Interplanetary Society.

The space probe is used mostly for the acquisition of scientific data enriching general knowledge on properties of outer space and heavenly bodies. Each probe (sometimes a series of several identical craft) is constructed to meet specific goals of a particular mission, and thus, represents a unique and sophisticated creation of contemporary engineering. Nevertheless, whether it is an Earth **satellite**, a crewed flight, or an automated probe, there are some common problems underlying any space mission: how to get to the destination point, how to collect the information required, and, finally,



Voyager space probe. *U.S. National Aeronautics and Space Administration (NASA).*

how to transfer the information back to Earth. Successful resolution of these principal issues is impossible without a developed net of high-tech Earth-based facilities used for assembling and testing the spacecraft-rocket system, for launching the probe into the desired trajectory, and for providing necessary control of probe-equipment operation, as well as for receiving data transmitted back to Earth.

As compared to crewed flights, automated space missions are far more economical and, of course, less risky to human life.

A probe's journey into far space can be divided into several stages. First, the probe has to overcome Earth's **gravity**. Escape velocities vary for different types of trajectories. During the second stage, the probe continues to move under the influence of its initial momentum and the combined gravitational influences of the **Sun** and bodies with substantial mass near its flight path. The third (approach) stage starts when the probe falls under the gravitational attraction of its destination target. The calculation of the entire trajectory from Earth to the point of destination is a complicated task. It must take into consideration numerous mutually conflicting demands: to maximize the payload but to minimize the cost, to shorten mission duration but to avoid such hazards as solar flares or meteoroid swarms, to remain within the range of the communication system but to avoid the unfavorable influence of large spatial bodies, etc.

Sometimes, strong gravitational fields of planets can be utilized to increase the probe's velocity and to change its direction considerably without firing the engines and using fuel. For instance, if used properly, Jupiter's massive gravitational pull can accelerate a probe enough to leave the **solar system** in any direction. The gravitational assistance or "swing-by" effect was successfully used, for example, in the American missions to Mercury via Venus, and in the voyage of the *Galileo* craft to Jupiter.

Projecting of payloads into designated trajectories is achieved by means of expendable launch vehicles (ELVs). A wide variety of ELVs possessed by the United States uses the same basic technology—two or more rocket-powered stages that are discarded when their engine burns are completed. Similar to the operation of a jet aircraft, the motion of a rocket is caused by a continuous ejection of a stream of hot gases in the opposite direction. The rocket's role as a prime mover makes it very important for the system's overall performance and cost. Out of 52 space-probe missions launched in the United States during the period from 1958 to 1988, 13 failed because of launch vehicle failures and only five because of probe equipment's malfunctions.

All supporting Earth-based facilities can be divided into three major categories: test grounds, where the spacecraft and its components are exposed to different extreme conditions to make sure that they are able to withstand tough stresses of outer space; check-out and launch ranges, where the lift-off procedure is preceded by a thorough examination of all spacecraft-rocket interfaces; and post-launch facilities, which are used to track, communicate with, and process the data received from the probe.

Hundreds of people and billions of dollars worth of facilities are involved in following the flight of each probe and in intercepting the data it transmits toward Earth. Already-developed facilities always have to be adopted in accordance with the specific spacecraft design. Today, the United States, Russia, and France (for unmanned flights only) possess major launch ranges, worldwide tracking networks, and dozens of publicly and privately owned test facilities. China is also actively developing space launch facilities and, in 1999, launched its first unmanned test of a program designed to enable China to launch a manned mission by 2003.

Any space probe is a self-contained piece of machinery designed to perform a variety of prescribed complex operations for a long time, sometimes for decades. There are ten major constituents of the spacecraft entity that are responsible for its vital functions: (1) power supply, (2) propulsion, (3) attitude control, (4) environmental control, (5) computer subsystem, (6) communications, (7) engineering, (8) scientific instrumentation, (9) guidance control, and (10) structural platform.

(1) The power supply provides well-regulated electrical power to keep the spacecraft active. Usually the solar-cell arrays transforming the Sun's illumination into **electricity** are used. Far from the Sun, where **solar energy** becomes too feeble, electricity may be generated by nuclear power devices. (2) The propulsion subsystem enables the spacecraft to maneuver when necessary, either in space or in a planet's atmosphere, and has a specific configuration depending upon the mission's goals. (3) The attitude-control subsystem allows orientation of the spacecraft for a specific purpose, such as to aim solar panels at the Sun, antennas at Earth, and sensors at scientific targets. It also aligns engines in the proper direction during the maneuver. (4) The environmental-control subsystem maintains the **temperature**, pressure, radiation and **magnetic field** inside the craft within the acceptable levels to secure proper functioning of equipment. (5) The computer subsystem performs data processing, coding, and storage along with routines for internal checking and maintenance. It times and initiates the pre-programmed actions independently of Earth. (6) The communication subsystem transmits data and receives commands from Earth. It also transmits identifying signals that allow ground crews to track the probe. (7) The engineering-instrumentation subsystem continuously monitors the "health" of the spacecraft's "organism" and submits status reports to Earth. (8) The scientific-instrumentation subsystem is designed to carry out the experiments selected for a particular mission, for example, to explore planetary geography, **geology**, atmospheric **physics** or electromagnetic environment. (9) The guidance-and-control subsystem is supposed to detect deviations from proper performance, determine corrections and to dispatch appropriate commands. In many respects, this subsystem resembles a human brain, since it makes active decisions, having analyzed all available information on the spacecraft's status. (10) The structural subsystem is a skeleton of the spacecraft; it supports, unites and protects all other subsystems.

Depending upon a mission's target, the probes may be classed as lunar, solar, planetary (Mercurian, Venusian, Martian, Jovian) or interplanetary probes. Another classification is based upon the mission type: flyby, orbiter, or soft-lander.

See also Astronomy; History of manned space exploration; Space and planetary geology; Spacecraft, manned

SPACE SHUTTLE

The **space** shuttle is a reusable spacecraft that takes off like a rocket, travels around the earth like a spacecraft, and then lands once again like a glider. The first space shuttle was the *Columbia*, whose maiden voyage took place in April 1981. Four additional shuttles were later added to the fleet: *Discovery*, *Challenger*, *Atlantis*, and *Endeavor*. The first shuttle launched by the Soviet Union (now Russia) was *Buran*, which made its debut in November 1988.

At one time, both the United States and the Soviet Union envisioned complex space programs that included two parts: (1) space stations orbiting around Earth and/or other planets, and (2) shuttle spacecraft that would transport humans, equipment, raw materials, and finished products to and from the space station. For economic reasons, each nation eventually ended up concentrating on only one aspect of the complete program. The Soviets built and for many years operated advanced space stations (*Salyut* and *Mir*), while Americans have focused their attention on the shuttle system.

The shuttle system has been given the name Space Transportation System (STS), of which the shuttles have been the key element. Initially lacking a space station with which to interact, the American shuttles operated with two major goals: (1) the conduct of scientific experiments in a zero-gravity environment, and (2) the launch, capture, repair, and release of satellites.

Now an international program, STS depends heavily on the contributions of other nations in the completion of its basic missions. For example, its Spacelab modules—the areas in which astronauts carry out most of their experiments—are designed and built by the European Space Agency, and the extendable arm used to capture and release satellites—the remote manipulator system or Canadarm—is constructed in Canada.

The space shuttle has four main parts: (1) the orbiter (2) the three main engines attached to the orbiter (3) two solid rocket engines, and (4) an external fuel tank. Although the Russian *Buran* differs in some details from the U.S. space shuttle fleet, the main features of all shuttles are similar.

The orbiter is approximately the size of a commercial DC-9 airplane with a length of 121 ft (37 m) and a wing span of 78 ft (23 m). Its net weight is about 161,000 lb (73,200 kg).

It is sub-divided into two main parts: the crew cabin and the cargo bay. The upper level of the crew cabin is the flight deck from which astronauts control the spacecraft's flight in orbit and during descent. Below the flight deck are the crew's personal quarters, containing personal lockers, sleeping, eating, and toilet facilities, and other necessary living units. The crew cabin is physically isolated from the cargo bay and is provided with **temperature** and pressure conditions similar to those on Earth's surface. The cabin's atmosphere is maintained with a composition equivalent to that of near-Earth atmosphere, 80% nitrogen and 20% **oxygen**.

The cargo bay is a large space 15 ft (4.5 m) by 60 ft (18 m) in which the shuttle's payloads are stored. The cargo bay can hold up to about 65,000 lb (30,000 kg) during ascent, although it is limited to about half that amount during descent.

In 1973, an agreement was reached between NASA and the European Space Agency (ESA) for the construction by ESA of a pressurized work space that could be loaded into the shuttle's cargo bay. The workspace, designated as Spacelab, was designed for use as a science laboratory in which a wide array of experiments could be conducted. Each of these Spacelab modules is 8.9 ft (2.7 m) long and 13 ft (3.9 m) in diameter. The equipment needed to carry out experiments is arranged in racks along the walls of the Spacelab, and the whole module is then loaded into the cargo bay of the shuttle prior to take-off. When necessary, two Spacelab modules can be joined to form a single, larger work space.

The power needed to lift a space shuttle into orbit comes from two solid-fuel rockets, each 149 ft (45.5 m) in length and 12 ft (4 m) in diameter, and the shuttle's own liquid-fuel engines. The fuel used in the solid rockets is composed of finely-divided **aluminum**, ammonium perchlorate, and a special polymer designed to form a rubbery mixture. The mixture is molded in such a way as to produce an 11-point starred figure. This shape exposes the maximum possible surface **area** of fuel during ignition, making combustion as efficient as possible within the engine.

The two solid-fuel rockets carry 1.1 million lb (500,000 kg) of fuel each, and burn out completely only 125 seconds after the shuttle leaves the launch pad. At solid-engine burnout, the shuttle is at an altitude of 161,000 ft (47,000 m) and 244 nautical miles (452 km) down range from launch site. At that point, explosive charges holding the solid rockets to the main shuttle go off and detach the rockets from the shuttle. The rockets are then returned to Earth by means of a system of parachutes that drops them into the Atlantic Ocean at a speed of 55 mi (90 km) per hour. The rockets can then be collected by ships, returned to land, refilled, and re-used in a later shuttle launch.

The three liquid-fueled shuttle engines have been described as the most efficient engines ever built by humans. At maximum capacity, they achieve 99% efficiency during combustion. They are supplied by fuel (liquid hydrogen) and oxidizer (liquid oxygen) stored in the 154 ft (46.2 m) external fuel tank. The fuel tank itself is sub-divided into two parts, one of which holds the liquid oxygen and the other, the liquid hydrogen. The fuel tank is maintained at the very low temperature (less than –454°F [–270°C]) necessary to keep hydrogen and oxygen in their liquid states. The two liquids are pumped into the shuttle's three engines through 17 in (43 cm) diameter lines that carry 1,035 gal (3,900 l) of fuel per second. Upon ignition, each of the liquid-fueled engines delivers 75,000 horsepower of thrust.

The three main engines burn out after 522 seconds, when the shuttle has reached an altitude of 57 nautical miles (105 km) and is down range 770 nautical miles (1,426 km) from the launch site. At this point, the external fuel tank is also jettisoned. Its return to the earth's surface is not controlled, however, and it is not recoverable for future use.

Final orbit is achieved by means of two small engines, the Orbital Maneuvering System (OMS) Engines located on external pods at the rear of the orbiter's body. The OMS engines are fired first to insert the orbiter into an elliptical orbit with an apogee of 160 nautical miles (296 km) and a perigee of 53 nautical miles (98 km) and then again to accomplish its final circular orbit with a radius of 160 nautical miles (296 km).

Humans and machinery work together to control the movement of the shuttle in orbit and during its descent. For making fine adjustments, the spacecraft depends on six small vernier jets, two in the nose and four in the OMS pods of the spacecraft. These jets allow human or computer to make modest adjustments in the shuttle's flight path in three directions.

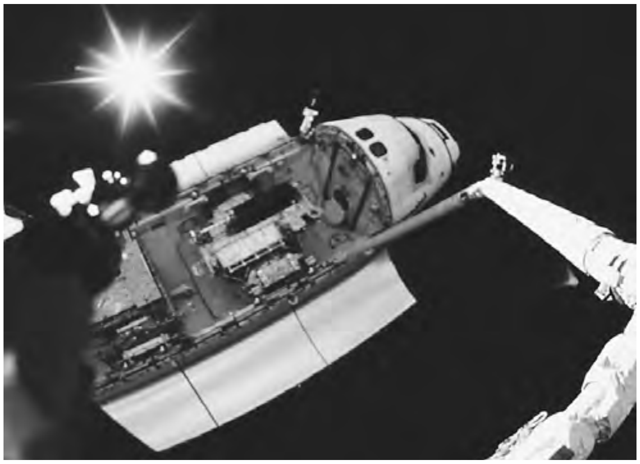
The computer system used aboard the shuttle is an example of the redundancy built into the spacecraft. Five discrete computers are used, four networked with each other using one computer program, and one operating independently using a different program. The four linked computers constantly communicate with each other, testing each other's decisions and deciding when one (or two or three) is not performing properly and eliminating that computer (or those computers) from the decision-making process. In case all four of the interlinked computers malfunction, decision-making is turned over automatically to the fifth computer.

This kind of redundancy is built into every essential feature of the shuttle's operation. For example, three independent hydraulic systems are available, all operating with independent power systems. The failure of one or even two of the systems does not, therefore, place the shuttle in a critical failure mode.

The space shuttles have performed a myriad of scientific and technical tasks in their nearly two decades of operation. Many of these have been military missions about which we have relatively little information. The launching of military spy satellites is an example of these.

Some examples of the kinds of activities carried out during shuttle flights include the following:

- After the launch of the *Challenger* shuttle (STS-41B) on February 3, 1984, astronauts Bruce McCandless II and Robert L. Stewart conducted the first ever untethered space walks using Manned Maneuvering Unit backpacks that allowed them to propel themselves through space near the shuttle. The shuttle also released into orbit two communication satellites, the Indonesian *Palapa* and the American *Westar* satellites. Both satellites failed soon after release but were recovered and



Space shuttle *Endeavour*. *U.S. National Aeronautics and Space Administration (NASA).*

returned to Earth by the *Discovery* during its flight that began on November 8, 1984.

- During the flight of *Challenger* (STS-51B) that began on April 29, 1985, crew members carried out a number of experiments in Spacelab 3 determining the effects of zero **gravity** on living organisms and on the processing of materials. They grew **crystals** of mercury (II) oxide over a period of more than four days, observed the behavior of two monkeys and 24 rats in a zero-gravity environment, and studied the behavior of liquid droplets held in suspension by sound waves.
- The mission of STS-51I (*Discovery*) was to deposit three communications satellites in orbit. On the same flight, astronauts William F. Fisher and James D. Van Hoften left the shuttle to make repairs on a Syncom **satellite** that had been placed in orbit during flight STS-51D but that had then malfunctioned.

Some of the most difficult design problems faced by shuttle engineers were those created during the reentry process. When the spacecraft has completed its mission in space and is ready to leave orbit, its OMS fires just long enough to slow the shuttle by 200 mi (320 km) per hour. This modest change in speed is enough to cause the shuttle to drop out of its orbit and begin its descent to Earth.

The re-entry problems occur when the shuttle reaches the outermost regions of the upper atmosphere, where significant amounts of atmospheric gases are first encountered. Friction between the shuttle—now traveling at 17,500 mi (28,000 km) per hour—and air molecules causes the spacecraft's outer surface to begin to heat up. Eventually, it reaches a temperature of 3,000°F (1,650°C).

Most materials normally used in aircraft construction would melt and vaporize at these temperatures. It was necessary, therefore, to find a way of protecting astronauts inside the shuttle cabin from this searing heat. The solution invented was to use a variety of insulating materials on the shuttle's outer skin. Parts less severely heated during re-entry are covered with 2,300 flexible quilts of a silica-glass composite. The more sensitive belly of the shuttle is covered with 25,000 insulating tiles, each 6 in (15 cm) square and 5 in (12 cm) thick, made of a silica-borosilicate **glass** composite.

The portions of the shuttle most severely stressed by heat—the nose and the leading edges of the wings—are coated with an even more resistant material known as carbon-carbon. Carbon-carbon is made by attaching a carbon-fiber cloth to the body of the shuttle and then baking it to convert it to a pure **carbon** substance. The carbon-carbon is then coated to prevent oxidation of the material during descent.

Once the shuttle reaches Earth's atmosphere, it ceases to operate as a rocket ship and begins to function as a glider. Its movements are controlled by aerodynamic controls, such as the tail rudder, a large flap beneath the main engines, and elevons, small flaps on its wings. These devices allow the shuttle to descend to the earth traveling at speeds of 8,000 mi (13,000 km) per hour, while dropping vertically at the rate of 140 mi (225 km) per hour. When the aircraft finally touches down, it is traveling at a speed of about 190 knots (100 m per second), and requires about 1.5 mi (2.5 km) to come to a stop.

Disasters have been associated with aspects of both the Soviet and American space programs. Unfortunately, the Space Transportation System has been no different in this respect. Mission STS-51L was scheduled to take off on January 28, 1986 using the shuttle *Challenger*. Only 72 seconds into the flight, the shuttle's external tank exploded, and all seven astronauts on board were killed.

The *Challenger* disaster prompted one of the most comprehensive studies of a major accident ever conducted. On June 6, 1986, the Presidential Commission appointed to analyze the disaster published its report. The reason for the disaster, according to the commission, was the failure of an O-ring at a **joint** connecting two sections of one of the solid rocket engines. Flames escaping from the failed joint reached the external fuel tank, set it on fire, and then caused an explosion of the whole spacecraft.

As a result of the *Challenger* disaster, a number of design changes were made in the shuttle. Most of these (254 modifications in all) were made in the orbiter. Another 30 changes were made in the solid rocket booster, 13 in the external tank, and 24 in the shuttle's main engine. In addition, an escape system was developed that would allow crew members to abandon a shuttle in case of emergencies, and NASA re-examined and redesigned its launch-abort procedures. Also, NASA was instructed to reassess its ability to carry out the ambitious program of shuttle launches that it had been planning.

The U.S. Space Transportation System was essentially shut down for a period of 975 days while NASA carried out necessary changes and tested new systems. Then, on September 29, 1988, the first post-*Challenger* mission was launched, STS-26. On that flight, *Discovery* carried NASA's TDRS-C communications satellite into orbit, putting the American STS program back on schedule once more.

In December, 1988, the crew of NASA's Space Shuttle STS-88 began construction of the **International Space Station** (ISS). By joining the Russian-made control module *Zarya* with the United States-built connecting module *Unity,* the crew of the *Endeavor* became the first crew aboard the ISS. Since the STS-88 mission, twelve more U.S. shuttle missions have led the construction of the International Space Station, a permanent laboratory orbiting 220 miles above Earth.

See also Space and planetary geology; Space physiology; Space probe; Spacecraft, manned

SPACECRAFT, MANNED

Manned spacecraft are vehicles with the capability of maintaining life outside of Earth's atmosphere. Partially in recognition of the fact that women as well as men are active participants in **space** travel programs, manned spacecraft are now frequently referred to as crewed spacecraft.

In its earliest stages, crewed space flight was largely an exercise in basic research. Scientists were interested in collecting fundamental information about the **Moon**, the other planets in our **solar system**, and outer space. Today, crewed space flight is also designed to study a number of practical problems, such as the behavior of living organisms and inorganic materials in zero **gravity** conditions.

A very large number of complex technical problems must be solved in the construction of spacecraft that can carry humans into space. Most of these problems can be classified in one of three major categories: communication, environmental and support, and re-entry.

Communication refers to the necessity of maintaining contact with members of a space mission as well as monitoring their health and biological functions and the condition of the spacecraft in which they are traveling. Direct communication between astronauts and cosmonauts can be accomplished by means of radio and television messages transmitted between a spacecraft and ground stations. To facilitate these communications, receiving stations at various locations around Earth have been established. Messages are received and transmitted to and from a space vehicle by means of large antennas located at these stations.

Many different kinds of instruments are needed within the spacecraft to monitor cabin **temperature**, pressure, **humidity**, and other conditions as well as biological functions such as heart rate, body temperature, blood pressure, and other vital functions. Constant monitoring of spacecraft hardware is also necessary. Data obtained from these monitoring functions is converted to radio signals that are transmitted to Earth stations, allowing ground-based observers to maintain a constant check on the status of both the spacecraft and its human passengers.

The fundamental requirement of a crewed spacecraft is, of course, to provide an atmosphere in which humans can survive and carry out the jobs required of them. This means, foremost, providing the spacecraft with an Earth-like atmosphere in which humans can breathe. Traditionally, the Soviet Union has used a mixture of nitrogen and **oxygen** gases somewhat like that found in the earth's atmosphere. American spacecraft, however, have employed pure oxygen atmospheres at pressures of about 5 lb per square inch, roughly one-third that of normal air pressure on the earth's surface.

Apollo 11 **Command and Service Modules. *Apollo 11* was the first mission to land mankind on another celestial body. *U.S. National Aeronautics and Space Administration (NASA).***

The level of **carbon dioxide** within a spacecraft must also be maintained at a healthy level. The most direct way of dealing with this problem is to provide the craft with a base, usually lithium hydroxide, which will absorb **carbon** dioxide exhaled by astronauts and cosmonauts. Humidity, temperature, odors, toxic gases, and sound levels are other factors that must be controlled at a level congenial to human existence.

Food and **water** provisions present additional problems. The space needed for the storage of conventional foodstuffs is prohibitive for spacecraft. Thus, one of the early challenges for space scientists was the development of dehydrated foods or foods prepared in other ways so that they would occupy as little space as possible. Space scientists have long recognized that food and water supplies present one of the most challenging problems of long-term space travel, as would be the case in a space station. Suggestions have been made, for example, for the purification and recycling of urine as drinking water and for the use of exhaled carbon dioxide in the growth of plants for foods in spacecraft that remain in orbit for long periods of time.

An important aspect of spacecraft design is the provision for power sources needed to operate communication, environmental, and other instruments and devices within the vehicle. The earliest crewed spacecrafts had simple power systems. The Mercury series of vehicles, for example, were powered by six conventional batteries. As spacecraft increased in size and complexity, however, so did their power needs. The Gemini spacecrafts required an additional conventional battery and two fuel cells, while the Apollo vehicles were provided with five batteries and three fuel cells.

One of the most serious on-going concerns of space scientists about crewed flights has been their potential effects on the human body. An important goal of nearly every space flight has been to determine how the human body reacts to a zero-gravity environment.

At this point, scientists have some answers to that question. For example, we know that one of the most serious dangers posed by extended space travel is the loss of calcium from bones. Also, the absence of gravitational forces results in a space traveler's blood collecting in the upper part of his or her body, especially in the left atrium. This knowledge has led to the development of special devices that modify the loss of gravitational effects during space travel.

One of the challenges posed by crewed space flight is the need for redundancy in systems. Redundancy means that there must be two or three of every instrument, device, or spacecraft part that is needed for human survival. This level of redundancy is not necessary with uncrewed spacecraft where failure of a system may result in the loss of a **space probe**, but not the loss of a human life. It is crucial, however, when humans travel aboard a spacecraft.

An example of the role of redundancy was provided during the *Apollo 13* mission. That mission's plan of landing on the Moon had to be aborted when one of the fuel cells in the service module exploded, eliminating a large part of the spacecraft's power supply. A back-up fuel cell in the lunar module was brought on line, however, allowing the spacecraft to return to Earth without loss of life.

Space suits are designed to be worn by astronauts and cosmonauts during take-off and landing and during extravehicular activities (EVA). They are, in a sense, a space passenger's own private space vehicle and present, in miniature, most of the same environmental problems as does the construction of the spacecraft itself. For example, a space suit must be able to protect the space traveler from marked changes in temperature, pressure, and humidity, and from exposure to radiation, unacceptable solar glare, and micrometeorites. In addition, the space suit must allow the space traveler to move about with relative ease and to provide a means of communicating with fellow travelers in a spacecraft or with controllers on the earth's surface. The removal and storage of human wastes is also a problem that must be solved for humans wearing a space suit.

Ensuring that astronauts and cosmonauts are able to survive in space is only one of the problems facing space scientists. A spacecraft must also be able to return its human passengers safely to Earth's surface. In the earliest crewed spacecrafts, this problem was solved simply by allowing the vehicle to travel along a ballistic path back to Earth's atmosphere and then to settle on land or sea by means of one or more large parachutes. Later spacecraft were modified to allow pilots some control over their re-entry path. The space shuttles, for example, can be piloted back to Earth in the last stages of re-entry in much the same way that a normal airplane is flown.

Perhaps the most serious single problem encountered during re-entry is the heat that develops as the spacecraft returns to Earth's atmosphere. Friction between vehicle and air produces temperatures that approach 3,092°F (1,700°C). Most **metals** and alloys would melt or fail at these temperatures. To deal with this problem, spacecraft designers have developed a class of materials known as ablators that absorb and then radiate large amounts of heat in brief periods of time. Ablators have been made out of a variety of materials, including phenolic resins, epoxy compounds, and silicone rubbers.

Some scientists are beginning to plan beyond **space shuttle** flights and the **International Space Station**. While NASA's main emphasis for some time will be unmanned probes and robots, the most likely target for a manned spacecraft will be Mars. Besides issues of long-term life support, any such mission will have to deal with long-term exposure to space radiation. Without sufficient protection, galactic cosmic rays would penetrate spacecraft and astronaut's bodies, damaging their DNA and perhaps disrupting nerve cells in their brains over the long-term. (Manned flights to the Moon were protected from cosmic rays by the earth's magnetosphere.) Shielding would be necessary, but it is always a trade-off between human protection and spacecraft weight. Moreover, estimates show it could add billions of dollars to the cost of any such flight.

See also Space and planetary geology; Space physiology

SPECTROSCOPY

Geoscientists utilize a number of different spectroscopy techniques in the study of Earth materials. The absorption, emission, or scattering of electromagnetic radiation by atoms or molecules is referred to as spectroscopy. A transition from a lower energy level to a higher level with transfer of electromagnetic energy to the **atom** or molecule is called absorption; a transition from a higher energy level to a lower level is called emission (if energy is transferred to the electromagnetic field); and the redirection of light as a result of its interaction with matter is called scattering.

When atoms or molecules absorb electromagnetic energy, the incoming energy transfers the quantized atomic or molecular system to a higher energy level. Electrons are promoted to higher orbitals by ultraviolet or visible light; vibrations are excited by infrared light, and rotations are excited by microwaves. Atomic-absorption spectroscopy measures the concentration of an element in a sample, whereas atomic-emission spectroscopy aims at measuring the concentration of elements in samples.

Infrared spectroscopy has been widely used in the study of surfaces. The most frequently used portion of the infrared spectrum is the region where molecular vibrational frequencies occur. This technique was first applied around the turn of the twentieth century in an attempt to distinguish **water** of crystallization from water of constitution in solids.

Ultraviolet spectroscopy takes advantage of the selective absorbance of ultraviolet radiation by various substances. Ultraviolet instruments have also been used to monitor air and

water pollution, to analyze **petroleum** fractions, and to analyze pesticide residues. Ultraviolet photoelectron spectroscopy, a technique that is analogous to x-ray photoelectron spectroscopy, has been used to study valence electrons in gases.

Microwave spectroscopy, or molecular rotational resonance spectroscopy, addresses the microwave region and the absorption of energy by molecules as they undergo transitions between rotational energy levels. From these spectra, it is possible to obtain information about molecular structure, including bond distances and bond angles. One example of the application of this technique is in the distinction of trans and gauche rotational isomers. It is also possible to determine dipole moments and molecular collision rates from these spectra.

Although there are many other forms of spectroscopy (e.g., UV-VIS absorption spectroscopy, molecular fluorescence spectroscopy, etc.) many modern advances in inorganic and organic based studies have resulted from the development of nuclear magnetic resonance (NMR) technology. In NMR, resonant energy is transferred between a radio-frequency alternating **magnetic field** and a nucleus placed in a field sufficiently strong to decouple the nuclear spin from the influence of atomic electrons. Transitions induced between substates correspond to different quantized orientations of the nuclear spin relative to the direction of the magnetic field. Nuclear magnetic resonance spectroscopy has two subfields: broadline NMR and high resolution NMR. High resolution NMR has been used in inorganic and organic **chemistry** to measure subtle electronic effects, to determine structure, to study chemical reactions, and to follow the motion of molecules or groups of atoms within molecules.

Electron paramagnetic resonance is a spectroscopic technique similar to nuclear magnetic resonance except that microwave radiation is employed instead of radio frequencies. Electron paramagnetic resonance has been used extensively to study paramagnetic species present on various solid surfaces. These species may be metal ions, surface defects, or absorbed molecules or ions with one or more unpaired electrons. This technique also provides a basis for determining the bonding characteristics and orientation of a surface complex. Because the technique can be used with low concentrations of active sites, it has proven valuable in studies of oxidation states.

Atoms or molecules that have been excited to high energy levels can decay to lower levels by emitting radiation. For atoms excited by light energy, the emission is referred to as atomic fluorescence; for atoms excited by higher energies, the emission is called atomic or optical emission. In the case of molecules, the emission is called fluorescence if the transition occurs between states of the same spin, and phosphorescence if the transition takes place between states of different spin.

In x-ray fluorescence, the term refers to the characteristic x rays emitted as a result of absorption of x rays of higher frequency. In electron fluorescence, the emission of electromagnetic radiation occurs as a consequence of the absorption of energy from radiation (either electromagnetic or particulate), provided the emission continues only as long as the stimulus producing it is maintained.

The effects governing x-ray photoelectron spectroscopy were first explained by German-American physicist **Albert Einstein** (1879–1955) in 1905, who showed that the energy of an electron ejected in photoemission was equal to the difference between the photon and the binding energy of the electron in the target.

When electromagnetic radiation passes through matter, most of the radiation continues along its original path, but a tiny amount is scattered in other directions. Light that is scattered without a change in energy is called Rayleigh scattering; light that is scattered in transparent solids with a transfer of energy to the solid is called Brillouin scattering. Light scattering accompanied by vibrations in molecules or in the optical region in solids is called Raman scattering.

See also Astronomy; Atmospheric chemistry; Focused Ion Beam (FIB); Geochemistry; Mineralogy

SPRINGS

A site where **groundwater** emerges from the subsurface is known as a spring. Springs present the most familiar manifestation of groundwater, and have been utilized as drinking **water** sources throughout history. These natural features have sometimes been viewed mysteriously and the waters regarded as having therapeutic, medicinal, or magical properties. These misconceptions continue today, including the belief that spring water is of superior quality or purity. Fallacies such as this are exploited in the sales of beverages and other products. Unfortunately, water that flows naturally from the ground is conveyed with no more special properties than the same groundwater that is drawn from a nearby well. In fact, because of the exposure at the surface, spring water is potentially more easily contaminated than water drawn from a properly constructed well.

Springs can be classified based on their groundwater source (e.g., water-table springs and perched springs). **Water table** springs discharge where the land surface intersects the water table. Perched springs, however, flow from the intersection of the land surface with a local groundwater body that is separated from the main **saturated zone** below by a zone of relatively lower **permeability** and an **unsaturated zone**. In addition to the location of the water table, groundwater discharge at springs is commonly controlled by other factors such as stratigraphic contacts, **faults and fractures**, and cavern openings. The relationship of local **topography** and geologic structure to the point of groundwater discharge is one of the most common classification systems for springs.

Springs are also classified based on magnitude of discharge, chemical characteristics, water **temperature**, type of the groundwater flow system, and others. Because springs allow them to easily and directly access the groundwater, hydrogeologists often use information of this nature to help interpret the groundwater flow system of an **area**.

The quantity of discharge from a particular spring is determined by three variables: **aquifer** permeability, groundwater basin size, and quantity of recharge. The largest springs can have a discharge of over 1,000 cubic feet per second. However, springs of this size are rare. A spring with a dis-

Hot spring. © ***Buddy Mays/Corbis. Reproduced by permission.***

charge insufficient to support a small rivulet is referred to as a seep. The flow from a seep is commonly so low as to preclude measurement.

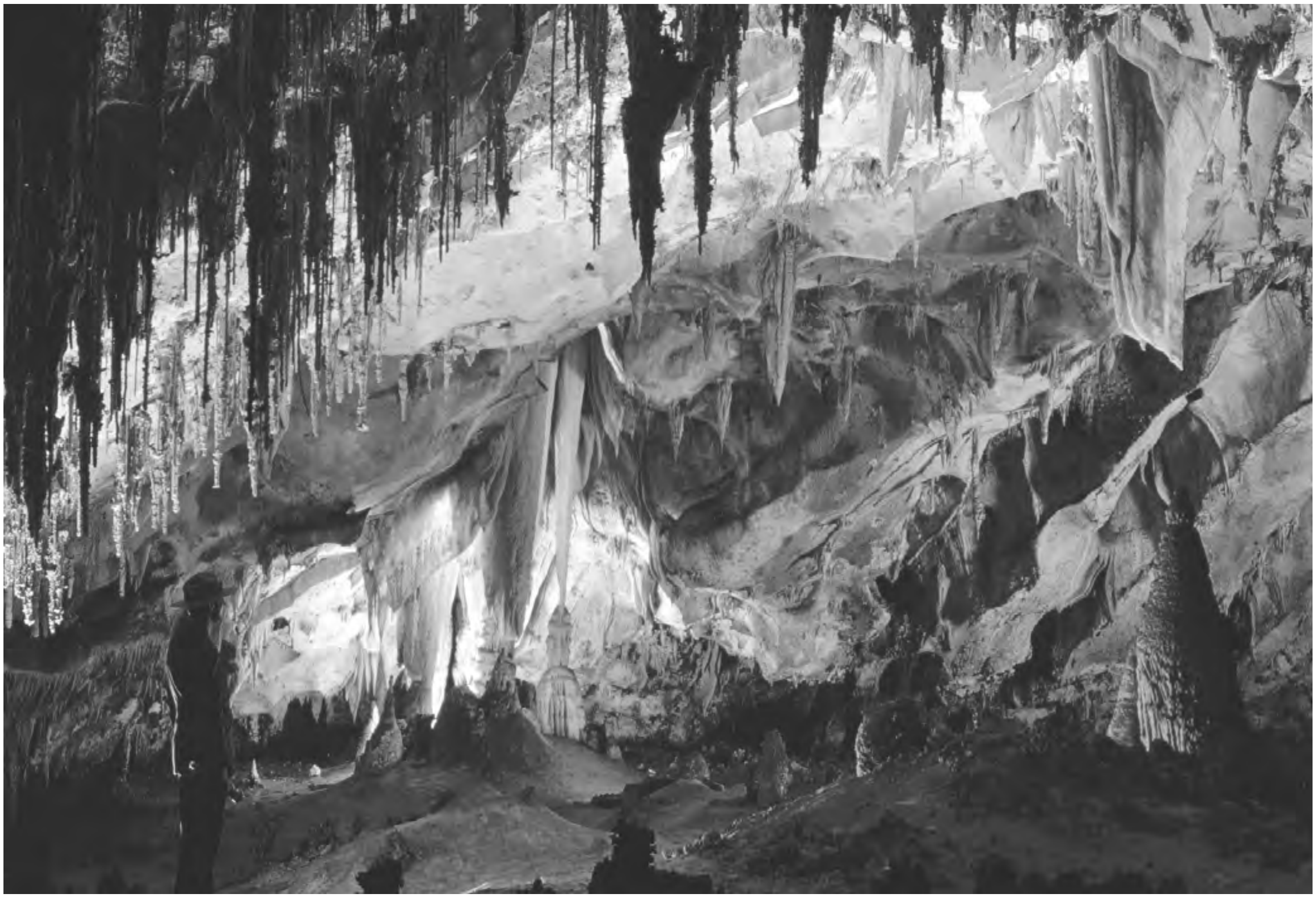
See also Karst topography; Porosity and permeability; Saturated zone

STALACTITES AND STALAGMITES

Stalactites and stalagmites are formed by **water** dripping or flowing from fractures on the ceiling of a **cave**. They are the most common types of speleothems in caves. In caves, stalagmites grow rather slowly—0.00028–0.037 in/yr (0.007–0.929 mm/yr)—while in artificial tunnels and basements they grow much faster. Soda straw stalactites are the fastest growing (up to 1.57 in/yr, 40 mm/yr), but most fragile stalactites in caves. Soda straw stalactites form along a drop of water and continue growing down from the cave ceiling forming a tubular stalactite, which resembles a drinking straw in appearance. Their internal diameter is exactly equal to the diameter of the water drop. Formation of most stalactites is initiated as soda straws. If water flows on their external surface, they begin to grow in thickness and obtain a conical form. If a stalactite curves along its length, it is called a deflected stalactite. If its curving is known to be caused by air currents, it is called anemolite. Petal-shaped tubular stalactites composed of aragonite are called spathites. When some stalactites touch each other they form a drapery with a curtain-like appearance.

When dripping water falls down on the floor of the cave it form stalagmites, which grow up vertically from the cave floor. Any changes in the direction of the growth axis of the stalagmite are suggestive of folding of the floor of the cave during the growth of the stalagmite. If a stalagmite is small, flat and round, it is called button stalagmite. Stalagmites resembling piled-up plates with broken borders are called pile-of-plates stalagmites. Rare varieties of stalagmites are mushroom stalagmites (partly composed of mud and having a mushroom shape), mud stalagmites (formed by mud) and lily pad stalagmites (resembling a lily pad on the surface of a pond). A calcite **crust** (shelfstone) grows around a stalagmite if it is flooded by a cave pool and forms a candlestick.

When a stalactite touches a stalagmite it forms a column. Usually, stalactites and stalagmites in caves are formed by calcite, less frequently by aragonite, and rarely by **gypsum**. Fifty-four other **cave minerals** are known to form rare stalac-



Carlsbad Caverns, Guadalupe Mountains, New Mexico. © *Adam Woolfitt/Corbis. Reproduced by permission.*

tites. Sometimes calcite stalactites or stalagmites are overgrown by aragonite **crystals**. This is due to **precipitation** of calcite that raises the ratio of magnesium to calcium in the solution enough that aragonite becomes stable.

Rarely, elongated single crystals or twins of calcite are vertically oriented and look like stalactites, but in fact are not stalactites because they are not formed by dripping or flowing water and don't have hollow channels inside. These elongated crystals are formed from water films on their surface.

In some volcanic **lava** tube caves exist lava stalactites and stalagmites that are not speleothems because they are not composed of secondary **minerals**. They are primary forms of the cooling, dripping lava.

The internal structure of stalactites and stalagmites across their growth axis usually consists of concentric rings around the hollow channel. These rings contain different amounts of **clay** and other inclusions, and reflect drier and wetter periods. Clay rings reflect hiatuses of the growth of the sample. Stalagmites may be formed for periods ranging from a few hundreds years up to one million years. Stalactites and stalagmites in caves have such great variety of shapes, forms, and color that each of them is unique in appearance. At the same time, their growth rates are so slow that once broken, they cannot recover during a human life span of time. Thus, stalactites and stalagmites are considered natural heritage objects and are protected by law in most countries, and their collection, mining, and selling is prohibited.

See also Cave minerals and speleothems

STELLAR EVOLUTION

In astrophysics and **cosmology**, stellar **evolution** refers to the life history of stars that is driven by the interplay of internal pressure and **gravity**.

Essentially, throughout the life of a star a tension exists between the compressing force of the star's own gravity and the expanding pressures generated by the nuclear reactions taking place in its core. After cycles of swelling and contraction associated with the burning of progressively heavier nuclear **fuels**, the star eventually expends its useable nuclear fuel and resumes contraction under the force of its own gravity. There are three possible fates for such a collapsing star. The particular fate for any star is determined by the mass of the star left after blowing away its outer layers.

A star less than 1.44 times the mass of the **Sun** (termed the Chandrasekhar limit) collapses until the pressure compacted electron **clouds** exerts enough pressure to balance the compressing force of gravity. Such stars become white dwarfs that are contracted to a radius the size of a planet. This is the fate of most stars.

If a star retains between 1.4 and roughly three times the mass of the Sun, the pressure of the electron clouds is insufficient to stop the gravitational collapse and stars of this mass continue their collapse to become neutron stars. Although neutron stars are only a few miles across, they have enormous density. Within a neutron star the nuclear forces and the repulsion of the compressed atomic nuclei balance the crushing force of gravity.

With the most massive stars, however, there is no known force in the Universe that can stop the final gravitational collapse and such stars collapse to form a singularity—a geometrical point of infinite density. As such a star collapses, its gravitational field warps spacetime and a black hole forms around the singularity.

Gravitational collapse is the process which provides the energy required for star formation, which starts with hydrogen fusion in a protostar at a heat of over 15 million K. Gravity, always directed inwards, decreases the radius of interstellar gas clouds, causing them to collapse and form a protostar, the immediate precursor of a star. Interstellar gas is initially cold, but it is heated by the gravitational energy released by the cloud contraction process. The radius of the protostar will continue to shrink under the influence of gravity until enough internal gas pressure, always directed outwards, builds up to stabilize the collapse. At this stage, the protostar is still too cold for hydrogen fusion to be initiated. Protostars can be detected by infrared **spectroscopy** because the initial warming event releases infrared electromagnetic radiation. If the mass of the protostar is less than 0.08 solar masses, the **temperature** of its core never reaches the range required for **nuclear fusion** and the failed star becomes a brown dwarf.

If, however, the mass of the protostar exceeds 0.08 solar masses, hydrogen fusion can proceed and the protostar becomes a main sequence star, with average surface temperatures of 10,800°F (6,000°C) (the internal and coronal temperatures measure in the millions of degrees). Most stars in the Universe are main sequence stars and are found on the diagonal of a Hertzsprung-Russell diagram. The main sequence stage of star evolution is the most stable state a medium-sized star can reach, and it can last for billions of years as such stars undergo very gradual and slow changes in luminosity and temperature. This is because pressure and gravitational forces are in equilibrium and the core has reached the temperature required for the fusion of hydrogen to helium to proceed smoothly. The time spent by a star in the main sequence is a function of its mass. The more massive the star, the less time spent on the main sequence. Although massive stars have large amounts of fuel, hydrogen fusion proceeds so quickly that it is completed within a few hundred thousand years. The fate of such massive stars is to explode violently. Smaller stars fuse their hydrogen at a slower rate. The lightest stars created in the early history of the Universe, for example, are still on the main sequence. The Sun is approximately midway through its main sequence life.

A post-main sequence star has two distinct regions, consisting of a core of helium nuclei and electrons surrounded by an envelope of hydrogen. With two protons in its nucleus, helium requires a higher fusion temperature than the one at which hydrogen fusion is proceeding. Without a source of energy to increase its temperature, the core cannot counter the effect of gravitational collapse and it starts to collapse, heating up as it does. This heat is transferred to the fusing hydrogen layer, which increases the luminosity of the shell and causes it to expand. As it expands, the outer layers cool off. At this point, the star is characterized by expansion and cooling of its shell, which causes it to become redder with increased luminosity. This is termed the red giant phase. When the Sun reaches this stage, it will be large enough to include Mercury in its sphere and hot enough to evaporate Earth's **oceans**. The core temperature of a red giant is on the order of 100 million K, the threshold temperature for the fusion of helium into **carbon**. A red giant, however, is initially stable, as pressure and gravity reach equilibrium.

If helium continues to accumulate in the core as the outer portions of the hydrogen envelope continue to fuse, eventually the helium in the core starts fusing into carbon in a violent event referred to as a helium flash, lasting as little as a few seconds. During this phase, the star gradually blows away its outer atmosphere into an expanding shell of gas known as a planetary nebula.

A star takes thousands of years to go through the red giant phase, after which it evolves into a white dwarf. It is then a small, hot star with a surface temperature as high as 100,000 K that makes it glow white. Because of its small size, a white dwarf has a very high density. A white dwarf consists of those elements that were created in its previous evolutionary phases via nucelosynthesis. The original hydrogen was fused into helium then totally or partly fused into carbon. In addition, heavier elements fuse from the carbon. The temperature of a white dwarf is not high enough to initiate a new cycle of fusion. In time, it eventually becomes a black dwarf as it loses its residual heat over billions of years. The size of a white dwarf is limited by a process called electron degeneracy. Electron degeneracy is the stellar equivalent of the Pauli exclusion principle, as is neutron degeneracy. No two electrons can occupy identical states, even under the pressure of a collapsing star of several solar masses. For stellar masses smaller than about 1.44 solar masses, the energy from the gravitational collapse is not sufficient to produce the neutrons of a neutron star, so the collapse is effectively stopped. This maximum mass for a white dwarf is called the Chandrasekhar limit.

When a massive star has fused all of its hydrogen, gravitational collapse is capable of generating sufficient energy so that the core can begin to fuse helium nuclei to form carbon. If the process can go beyond the red giant stage, the star becomes a supergiant. Following fusion and disappearance of the helium, the core can successively burn carbon and other heavier elements until it acquires a core of **iron**, the heaviest element that can be formed by natural fusion. Another possible fate of white dwarfs is to evolve into novae or another type of super-novae. Novae occur in binary star systems in which one star is a white dwarf. If the companion star evolves into a red giant, it can expand far enough so that gas from its outer shell can be pulled onto the white dwarf. The white dwarf accumulates the additional gas until it reaches nuclear fusion temperatures, at which point the gas ignites explosively into a nova.

Alternatively, a white dwarf may accumulate enough material from its binary star to exceed the Chandrasekhar limit. This results in a sudden and total collapse of the white dwarf, with temperature increases in ranges capable of initiating rapid carbon fusion and subsequent explosion of the white dwarf into a spectacular supernova, that can shine with the brightness of 10 billion suns with a total energy output of ~10^{44} joules, equivalent to the total energy output of the Sun during its entire lifetime.

See also Astronomy; Big Bang theory; Bohr model of the atom; Cosmology; Quantum electrodynamics (QED); Solar sunspot cycles; Solar system; Stellar life cycle

STELLAR LIFE CYCLE

Until the last half of the nineteenth century, **astronomy** was principally concerned with the accurate description of the movements of planets and stars. Developments in electromagnetic theories of light along with the articulation of quantum and relativity theories at the start of the twentieth century, however, allowed astronomers to probe the inner workings of the stars. Of primary concern was an attempt to coherently explain the life cycle of the stars and to reconcile the predictions of advances in physical theory with astronomical observation. Profound questions regarding the birth and death of stars led to the stunning conclusion that, in a very real sense, life itself was a product of **stellar evolution**.

It is now known that the mass of a star determines the ultimate fate of a star. Stars that are more massive burn their fuel quicker and lead shorter lives. These facts would have astonished astronomers working at the dawn of the twentieth century. At that time an accurate understanding of the source of the heat and light generated by the **Sun** and stars suffered from a lack of understanding of nuclear processes.

Based on Newtonian concepts of **gravity**, many astronomers understood that stars were formed in **clouds** of gas and dust termed nebulae that were measured to be light years across. These great molecular clouds, so thick they are often opaque in parts, teased astronomers. Decades later, after development of **quantum theory**, astronomers were able to develop a better understanding of the energetics behind the “reddening” of light leaving stellar nurseries (reddened because the blue light is scattered more and the red light passes more directly through to the observer). Astronomers speculated that stars formed when regions of these clouds collapsed (termed gravitational clumping). As the region collapsed, it accelerated and heated up to form a protostar heated by gravitational friction.

The source of heat in stars in the pre-atomic age eluded astronomers who sought to reconcile seeming contradictions regarding how stars were able to maintain their size (i.e., not shrink as they burned fuel) and radiate the tremendous amounts of energy measured. In accord with dominant religious beliefs, the Sun, using conventional energy consumption and production concepts could be calculated to be less than a few thousand years old.

In 1913, Danish Astronomer Ejnar Hertzsprung (1873–1967) and English astronomer Henry Norris Russell (1877–1957) independently developed what is now known as the Hertzsprung-Russell diagram. In the Hertzsprung-Russell diagram, the spectral type (or, equivalently, color index or surface **temperature**) is placed along the horizontal axis and the absolute magnitude (or luminosity) along the vertical axis. Accordingly, stars are assigned places top to bottom in order of increasing magnitude (decreasing brightness) and from right to left by increasing temperature and spectral class.

The relation of stellar color to brightness was a fundamental advance in modern astronomy. The **correlation** of color with true brightness eventually became the basis of a widely used method of deducing spectroscopic parallaxes of stars that allowed astronomers to estimate how far distant stars are from the Earth (estimates from closer stars could be made by geometrical parallax).

In the Hertzsprung-Russell main sequence, stars (those later understood to be burning hydrogen as a nuclear fuel) form a prominent band or sequence of stars from extremely bright, hot stars in the upper left-hand corner of the diagram to faint, relatively cooler stars in the lower right-hand corner of the diagram. Because most stars are main sequence stars, most stars fall into this band on the Hertzsprung-Russell diagram. The Sun, for example, is a main-sequence star that lies roughly in the middle of the diagram among what are referred to as yellow dwarfs.

Russell attempted to explain the presence of giant stars as the result of large gravitational clumps. Stars, according to Russell, would move down the chart as they lost mass burned as fuel. Stars began life huge cool red bodies and then undergo a continual shrinkage as they heated. Although the Hertzsprung-Russell diagram was an important advance in understanding stellar evolution—and it remains highly useful to modern astronomers—Russell’s reasoning behind the movements of stars on the diagram turned out to be exactly the opposite of the modern understanding of stellar evolution made possible by an understanding of the Sun and stars as thermonuclear reactors.

Advances in quantum theory and improved models of atomic structure made it clear to early twentieth century astronomers that deeper understanding of the life cycle of stars and of cosmological theories explaining the vastness of **space** was to be forever tied to advances in understanding inner workings of the universe on an atomic scale. A complete understanding of the energetics of mass conversion in stars was provided by Albert Einstein’s (1879–1955) special theory of relativity and his relation of mass to energy (Energy = mass times the square of the speed of light).

The Orion Nebula in the constellation of Orion is a stellar nursery where new stars are created. The bright red star in Orion is Betelguese, a red giant approaching the end of its stellar life cycle. ***U.S. National Aeronautics and Space Administration (NASA).***

During the 1920s, based on the principles of quantum mechanics, British physicist Ralph H. Fowler determined that, in contrast to the predictions of Russell, a white dwarf would become smaller as its mass increased.

Indian-born American astrophysicist Subrahmanyan Chandrasekhar (1910–1995) first articulated the evolution of stars into supernova, white dwarfs, neutron stars and for predicting the conditions required for the formation of black holes, which were subsequently found in the later half of the twentieth century. Before the intervention of World War II, American physicist J. Robert Oppenheimer (1904–1967), who ultimately supervised Project Trinity (the making of the first atomic bombs), made detailed calculations reconciling Chandrasekhar's predictions with general **relativity theory**.

In the decade that followed, as the mechanisms of atomic fission and fusion worked their way into astronomical theory, it became apparent that stars spend approximately ninety percent of their lives as main sequence stars before the fate dictated by their mass becomes manifest.

Astronomers refined concepts regarding stellar birth. Eventually as a protostar contracts enough, the increase in its temperature triggers **nuclear fusion**, and the star becomes visible as it vaporizes the surrounding cocoon. Stars then lead the majority of their life as main sequence stars, by definition burning hydrogen as their nuclear fuel.

It was the death of the stars, however, that provided the most captivating consequences. Throughout the life of a star, a tensional tug-of-war exists between the compressing force of the star's own gravity and the expanding pressures generated by nuclear reactions at its core. After cycles of swelling and contraction associated with the burning of progressively heavier nuclear **fuels**, eventually the star runs out of useable nuclear fuel. The spent star then contracts under the pull of it own gravity. The ultimate fate of any individual star is determined by the mass of the star left after blowing away its outer layers during its paroxysmal death spasms.

Low mass stars could fuse only hydrogen, and when the hydrogen was used up fusion stopped. The expended star shrank to become a white dwarf.

Medium mass stars swell to become red giants, blowing off planetary nebulae in massive explosions before shrinking to white dwarfs. A star remnant less than 1.44 times the mass of the Sun (termed the Chandrasekhar limit) collapses until the pressure in the increasing compacted electron clouds exerts enough pressure to balance the collapsing gravitational force. Such stars become "white dwarfs" contracted to the radius of only a few thousand kilometers, roughly the size of a planet. This is the fate of the Sun.

High mass stars can either undergo **carbon** detonation or additional fusion cycles that create and then use increasingly heavier elements as nuclear fuel. Regardless, the fusion cycles can only use heavier elements up to **iron** (the main product of **silicon** fusion). Eventually, as iron accumulates in the core, the core can exceed the Chandrasekhar limit of 1.4 times the mass of the Sun and collapses. These preliminary theoretical understandings paved the way for many of the discoveries in the second half of the twentieth century when it was more fully understood that as electrons are driven into protons neutrons are formed and energy is released as gamma rays and neutrinos. After blowing off its outer layers in a supernova explosion (type II) the remnants of the star form a neutron star and/or pulsar (discovered in the late 1960s).

Although he did not completely understand the nuclear mechanisms (nor of course the more modern terminology applied to those concepts), Chandrasekhar's work allowed the prediction that such neutron stars would be only a few kilometers in radius and that within such a neutron star the nuclear forces and the repulsion of the compressed atomic nuclei balanced the crushing force of gravity. With more massive stars, however, there was no known force in the universe that could withstand the gravitational collapse. Such extraordinary stars would continue their collapse to form a singularity—a star collapsed to a point of infinite density. According to general relativity, as such, a star that collapses its gravitational field warps space time so intensely that not even light can escape and a black hole forms.

Although the modern terminology presented here was not the language of early twentieth century astronomers, German astronomer Karl Schwarzschild (1873–1916) made important early contributions to the properties of geometric space around a singularity when warped according to Einstein's general relativity theory.

There are several important concepts stemming from the evolution of stars that have enormous impact on science and philosophy in general. Most importantly, the articulation of the stellar evolutionary cycle had profound effects on the cosmological theories developed during the first half of the twentieth century that culminated with the **Big Bang theory**, first proposed by Russian physicist Alexander Friedmann (1888–1925) and Belgian astronomer Georges Lemaitre (1894–1966) in the 1920s and subsequently modified by Russian-born American physicist George Gamow (1904–1968) in the 1940s.

The observations and theories regarding the evolution of stars meant that only hydrogen, helium, and a perhaps a smattering of lithium were produced in the big bang. The heavier elements including, of course, carbon and **oxygen**, up to iron were determined to have their genesis in the cores of increasingly massive dying stars. The energy released in the supernova explosions surrounding stellar death created shock waves that gave birth via fusion to still heavier elements and allowed the creation of radioactive isotopes.

The philosophical implications of this were as startling as quantum and relativity theories underpinned the model. Essentially, all of the elements heavier than hydrogen that comprise man's everyday existence were literally cooked in a process termed nucleosynthesis that took place during the paroxysms of stellar death. Great supernova explosions scattered these elements across the Cosmos.

See also Cosmology

STELLAR MAGNITUDES

Of principle importance to general astronomical observation is the observable brightness of the stars. Magnitude is the unit used in **astronomy** to describe a star's brightness. Although stellar magnitude in the visible spectrum dictates which stars can be observed under particular visible light conditions—variable due to time of observation, **moon** phase, atmospheric conditions, and the amount of light pollution present—magnitude also describes the relative amount of electromagnetic radiation observable in other regions of the **electromagnetic spectrum** (e.g., the x ray region of the spectrum).

Stars emit different amounts of radiation in different regions of the spectrum, so a star's "brightness" or magnitude will differ from one part of the spectrum to the next. An important field of research in modern astronomy is the accurate measurement of stellar brightness in magnitudes in different parts of the spectrum.

The Greek astronomer Hipparchus devised the first magnitudes in the second century B.C. He classified stars according to how bright they looked to the eye: the brightest stars he called "1st class" stars, the next brightest "2nd class," and so on down to "6th class." In this way, all the stars visible to the ancient Greeks were neatly classified into six categories.

Modern astronomers still use Hipparchus' categories, though in considerably refined form. With modern instruments astronomers measure a quantity called *V*, the star's brightness in the visual portion of the spectrum. Since visual light is what our eyes detect, *V* is analogous to Hipparchus' classes. For example, Hipparchus listed Aldebaran, the brightest star in the constellation Taurus, as a 1st class star and modern astronomers measure Aldebaran's *V* at 0.85. Astronomers often refer to a star's visual brightness as its apparent magnitude, a description of how bright the star appears to the eye (or the **telescope**).

Hipparchus' scheme defined from the outset one of the quirks of magnitudes: they list magnitude inversely. The fainter the star, the larger the number describing its magnitude. Therefore, the **Sun**, the brightest object in the sky, has an apparent magnitude of –26.75, while Sirius, the brightest star in the sky other than the Sun and visible on cold winter nights in the constellation Canis Major, has an apparent magnitude of –1.45. The faintest star you can see without optical aid is about +5 or +6 in a very dark sky with little light pollution. The faintest objects visible to the most powerful telescopes on Earth have an apparent magnitude of about +30.

More revealing than apparent magnitude is absolute magnitude, the apparent magnitude a star would have if it were ten parsecs from the Earth (a parsec is a unit of distance equal to 12 trillion mi [19.3 trillion km]). This is important because apparent magnitude can be deceiving. You know that a penlight is not as bright as a streetlight, but if you hold the penlight near your eye, it will appear brighter than a streetlight six blocks away. That's why *V* is called apparent magnitude: it is only how bright the star appears to be. For example, the Sun is a fainter star than Sirius—Sirius emits far more energy than the Sun does—yet the Sun appears brighter because it is so much closer. The Sun has an absolute magnitude of +4.8, while Sirius is +1.4.

In 1856, the British scientist N. R. Pogson noticed that Hipparchus' 6th class stars were roughly 100 times fainter than his 1st class stars. Pogson redefined the stars' *V* brightness so that a difference of five magnitudes was exactly a factor of 100 in brightness. This meant that a star with $V = 1.00$ appeared to be precisely 100 times brighter than a star with $V = 6.00$. One magnitude is then a factor of about 2.512 in brightness.

The Sun ($V = -26.75$) has an apparent visual brightness 25 magnitudes greater than Sirius. The difference in apparent brightness between the Sun and the faintest object humans have ever observed (using the **Hubble Space Telescope**) is more than 56 magnitudes.

In the 140 years since Pogson created the modern magnitudes, astronomers have developed many different brightness systems. In 1953, H. L. Johnson created the *UBV system* of brightness measurements. *B* is the star's brightness in magnitudes measured in the blue part of the spectrum, while *U* is the brightness in the ultraviolet spectral region. There are many other brightness measurement systems in use.

Accurate measurement of stellar brightness is important because subtracting the brightness in one part of the spectrum from the brightness in another part reveals important information about the star. For many stars the quantity *B-V* gives a good approximation of the star's **temperature**. It was established in 1978 that the quantity *V-R*, where *R* is the brightness in the red part of the spectrum, can be used to estimate a star's radius.

See also Cosmology; Quantum electrodynamics (QED); Seeing

STENO, NICOLAS (1638-1686)

Danish geologist and anatomist

The son of a Copenhagen goldsmith, Nicolas Steno had a short but varied scientific career. His given name was Niels Stensen, but he is generally referred to by the Latinized version, Nicolas Steno. His name also has a variety of other spellings, such as Steensen, Stenonis (Latin), Stenone (Italian) and Stenon (French).

Steno's early schooling was accomplished in Copenhagen until 1660, when he began to travel **Europe** to study abroad. While a pupil of anatomy in Amsterdam, in the Netherlands, he discovered the parotid salivary duct, which is also called Stensen's duct. He made a number of other anatomical discoveries, including that muscles were made of fibrils, and he showed that the pineal gland existed in animals other than man. This was notable because some considered the pineal gland the location of the human soul, an idea first proposed by Rene Descartes (1596–1650), and so had considered it a gland unique to humans. In 1665, Steno moved to Florence, Italy, where his medical skills got him appointed physician to Grand Duke Ferdinand II of Tuscany. After returning to the Netherlands he was made Royal Anatomist in Copenhagen in 1672.

While in Italy, Steno was sent a huge shark's head that had been caught by local fishermen. While dissecting and studying it, Steno was struck by the similarity of the shark's teeth to common Mediterranean **fossils** known as 'tongue stones.' His study of these fossils led him to consider how any solid object could get inside another. In 1669, Steno published a short work that was to be an introduction to a larger study he never attempted, entitled *De solido intra solidum naturaliter contento dissertationis prodromus* (A preliminary discourse on a solid body contained naturally within a solid).

To illustrate his ideas, Steno made some of the earliest sketches of geological sections, and formulated three important geological principles. First, Steno noted that it was possible to tell which had been solid first, the **rock** or the fossil, by noting which was impressed on the other. In this way, Steno showed that the rocks must have formed around the fossils, and he suggested that the rocks had solidified out of former **seas**. Additionally, Steno argued that such rock layers would have formed in horizontal layers, and that any changes to the original horizontality must have occurred after their creation. Finally, Steno concluded that the oldest layers of rock strata must be those on the bottom, and newer layers were superposed on top of them. From this, Steno developed a geological history of rock formation, becoming one of the founders of **stratigraphy**.

Because the 'tongue stones' left an impression on the encasing rocks, Steno argued they had existed before the rock. Because they resembled shark's teeth so closely, he concluded that they were most likely ancient shark's teeth. Steno argued that similar fossils also had an organic origin, which went against the popular beliefs that such 'stones' had fallen from the sky, had grown from the Earth, or had more mystical origins.

Steno also made some important early studies of **crystals**. His observations of **quartz** showed that while different in appearance the quartz crystals all had the same corresponding angles between faces. He generalized this rule to all crystals, and the principle of constant angles in crystals is still known as Steno's law.

Steno had been raised a Lutheran, but in 1667, he converted to Catholicism. His faith caused him to abandon the study of science, and in 1677, he was appointed a titular bishop and spent the remainder of his days ministering to the few remaining Catholics in Northern Germany and Scandinavia.

See also Fossil record; Crystals and crystallography

STEVIN, SIMON (1548-1620)

Belgian-born Dutch mathematician and engineer

Simon Stevin (Latinized to Stevinus, as was the custom of the times) took as his motto, "Wonderful, yet not unfathomable," or, alternatively, "Nothing is the miracle it appears to be". In his pursuit to fulfill this motto, Stevinus made significant contributions to mathematics, engineering, and the earth sciences. As a mathematician, he was the first to advocate the use of tenths towards the establishment of decimals in mathematical calculations. As an engineer, he developed a method of releasing **floods** via Holland's vast canal system in the event of an invasion. The first achievement mentioned above has great bearing on mathematical calculations in the earth sciences and the second relates to a combination of engineering and the study of the behavior of running **water**. However, it was his contributions to hydrostatics, **astronomy**, **gravity**, and magnetic declination that established his importance to the development of the earth sciences.

Stevinus is often credited as the father of hydrostatics, the science that studies fluids at rest. Prior to his research, many scientists believed that the shape of a container of a liquid influenced the amount of pressure exerted by the liquid on its sides. By this reasoning, a circular lake might experience about the same water pressure all the way around the lake, but the pressure on the walls of a lake with an irregular shape would vary from one **area** to another. Stevinus mathematically demonstrated that only the area of the liquid's surface and its depth influenced the pressure against the sides. This information is often used by scientists in studying the engineering of wells and the **permeability** of rocks in the construction of dams as well as the strength of the dam itself.

One of his contributions to astronomy was his early defense of the Copernican model (a **Sun** centered **solar system**). Stevinus wrote in support of the heliocentric theory before Italian astronomer **Galileo Galilei** (1564–1642) came to the same conclusion. However, Stevinus had neither the telescopic evidence of Galileo nor the astronomical data of German astronomer **Johannes Kepler** (1571–1630) to add significantly to the argument.

Of greater significance to the science of astronomy was a discovery that produced new evidence regarding the relationship between gravity and falling bodies. This evidence would eventually become critical to the understanding of how the Sun holds the planets in their orbits and theories about the entire universe. The discovery was made by dropping two bodies of different weights from a high tower. Stevinus recorded that both objects struck the ground at the same time, despite their weight differences. This information disproved the assumption of Greek philosopher Aristotle (384–322 B.C.) that heavier objects fall faster than lighter objects under all circumstances, an assumption that had stood unchallenged for almost 2,000 years. Most historians argue that Stevinus performed this experiment, or at least played a part in arranging the experiment. Although he preceded Galileo by about three years in recording this discovery, his achievement was later attributed to Galileo. Today, many historians hold that Galileo was not only the first to record the experiment, but that he dropped the weights off the Leaning Tower of Pisa (there is no clear evidence that Galileo carried out such an experiment from the Leaning Tower). Regardless of who recorded the experiment first, it was a giant step away from Aristotelean thinking and eventually led to the Universal Law of Gravitation as outlined by English physicist Isaac Newton (1642–1727).

Stevinus' final contribution involved magnetic declination. Since the time of the Spanish-Italian navigator Christopher Columbus (1451–1506), it was a widely known fact that compasses did not point true north and south. Instead, they pointed toward what is known as the magnetic north and south poles. Because of this anomaly, the reliability of the compass depended on location. The difference between the magnetic poles and true north and south poles is known as the magnetic declination. By calculating and mapping magnetic declination, the navigator's job becomes much easier and more accurate. Realizing this, Stevinus was the first to undertake this task. At the time of his death he had calculated magnetic declination for 43 points on Earth's surface.

Stevinus' dedication to his motto and his work may have kept him from marrying until very late in life, or at least it would seem so. In his sixty-fourth year he finally married and eventually fathered four children before his death in 1620.

See also Gravitational constant; Hydrostatic pressure; Polar axis and tilt; Solar system

STOCK • *see* PLUTON AND PLUTONIC BODIES

STRATEGIC PETROLEUM RESERVE (GEOLOGIC CONSIDERATIONS)

The Strategic **Petroleum** Reserve (SPR) operated by the United States Department of Energy is the largest emergency supply system of its kind in the world. The SPR presently consists of four underground storage facilities located in salt domes along the coastal regions of Louisiana and Texas, and has a total storage capacity of 700 million barrels of oil. These sites were chosen from among the more than 400 potential areas along the Gulf Coast of the southern United States after careful review of their relative geologic characteristics.

A salt dome is a body of **rock** salt surrounded by layers of sedimentary rock. Geologic characteristics considered in selecting storage sites include: 1) **area** geologic activity, 2) structural size 3) existence of a trapping mechanism, 4) salt geometry, 5) salt composition, and 6) surface conditions.

Geologic activity in the area of potential storage sites must be well understood. The coastal plains along the Gulf Coast tend to be in a perpetual state of either subsidence or uplift, and the rate of such relative change must be measurable and predictable.

Structural size is a significant factor in SPR storage and location. Oil is stored in cylindrically shaped caverns constructed within the salt body that are typically 200 ft (61 m) in diameter and approximately 2,000 ft (610 m) in height or larger. A storage dome may consist of from one to more than twenty caverns in a three-dimensional pattern. Salt domes along the Gulf Coast typically range between being 0.5 to 5 miles in diameter and may be over 20,000 ft (6,096 m) in vertical height.

Fluid naturally flows through permeable strata just as **water** passes through a sponge. Oil will seek the highest possible level due to its relatively low specific **gravity** and would float to the surface if not otherwise trapped. A salt dome must be overlain by a trapping mechanism in order to be an environmentally safe and an economically secure storage site. Cap rock is a stratum of rock lacking **permeability** that can act as a trapping mechanism. However, not all salt domes are overlain by cap rock.

Salt domes are usually formed as the lighter salt rises through sedimentary strata above in a plastic state from a deeper source, while forming irregular-shaped and sometimes freestanding columns. The three-dimensional geometry of the salt diapir must be profiled in order to facilitate the design of the storage cavern pattern.

Ideally, the salt dome is composed of homogenous halite free of shale or other sedimentary rock. The presence of irregularities in composition may effect cavern construction and containment integrity.

Surface conditions play a role in site selection and project design, construction and ease of operation. Typically, such sites are located in marsh areas or beneath standing water. Proximity to existing infrastructure supporting oil import, delivery, and water handling is a major cost and operational consideration.

Though geologically complex, salt domes have proven to be a reliably safe and economically competitive means of storing oil for future use, and play a key role in national energy management and supply.

See also Petroleum detection; Petroleum, economic uses of; Petroleum extraction; Petroleum, history of exploration

STRATIFORM CLOUD • *see* CLOUDS AND CLOUD TYPES

STRATIGRAPHY

Stratigraphy is that subarea of **geology** that treats the description, **correlation**, and interpretation of stratified Earth materials. Typically, geologists consider stratified Earth materials as layers of sediment or sedimentary **rock**. This definition, however, clearly encompasses other materials such as volcanic **lava**, ash flows, ash-fall layers, meteoritic impact ejecta layers, and soils. In fact, using this definition, any material that obeys the law of **superposition** during its formation could be placed in the domain of stratigraphy. Generally, internal layers within Earth (**crust**, mantle, and core) are not considered the type of layers studied by stratigraphers because they formed by Earth's internal differentiation processes.

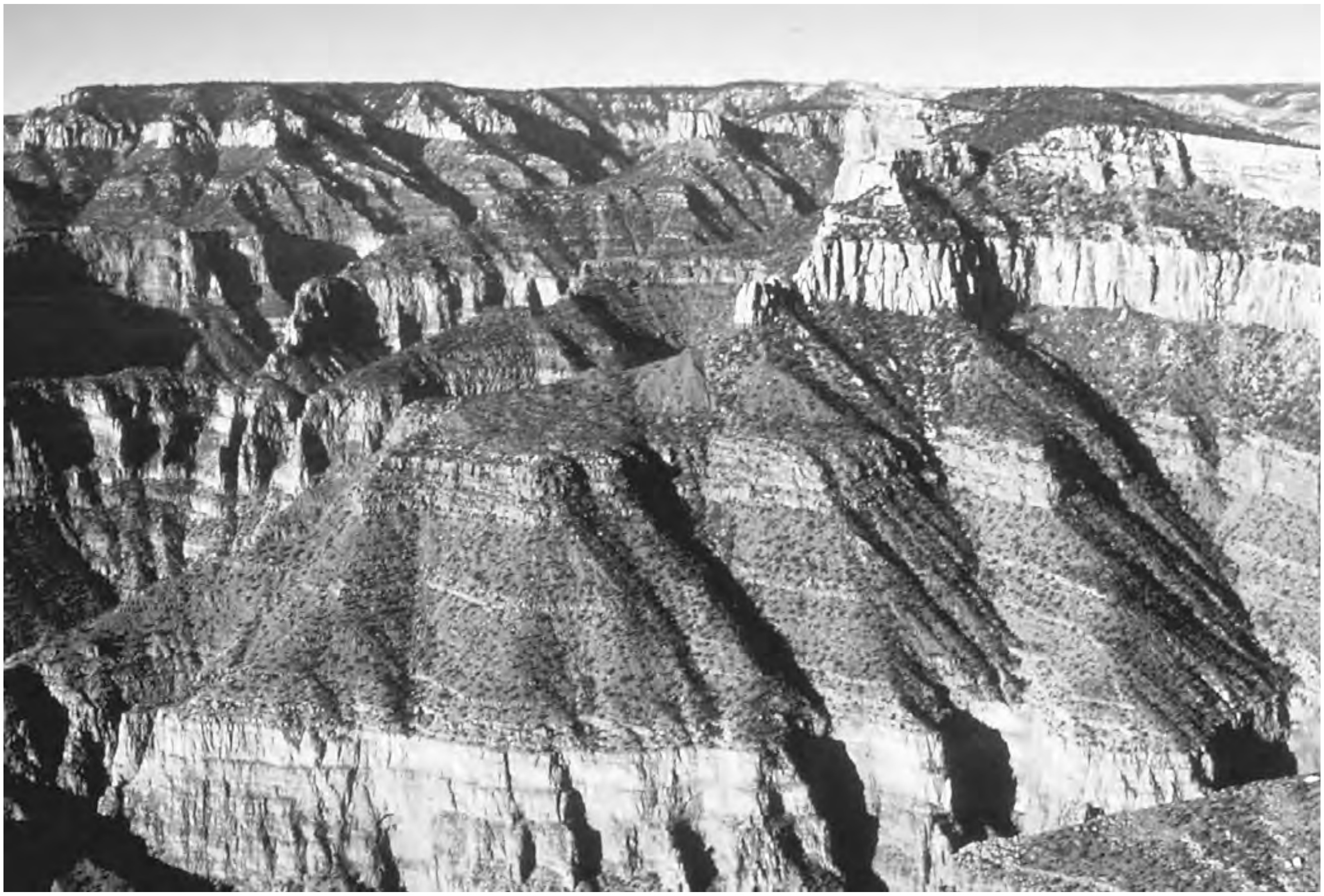
Some geologists give a broader definition to the term stratigraphy. Planetary geologists sometimes view stratigraphy as if it were the study of the sequence of events on a planet or moon's surface. In addition, stratigraphy has been broadly used by some geologists who study mountain building and **plate tectonics** to mean the study of order of emplacement of rock units of various types, including igneous and metamorphic rocks, to which the law of superposition does not apply. In some cases, stratigraphy is used to define the study of geologic history of an **area** or country, but it is more correct to say that stratigraphy is the practical foundation for **historical geology**. In this article, the concept of stratigraphy expressed in the first paragraph is viewed as best and most correct.

Stratigraphy had its origins in the Renaissance writings of Nicholas Steno (1638–1687), who was the first to write lucidly about sedimentary strata. He observed strata exposed in the Arno River valley of Italy, and noted three axiomatic ideas, which became known as the first three "laws" of stratigraphy (*Prodromus*, 1669). These laws are known today as superposition, lateral continuity, and original horizontality. Superposition holds that layers are deposited so that the older layer is on the bottom. Unless strata are disturbed, this is always true. Lateral continuity holds that sedimentary layers extend laterally until they become so thin that they end at a "feather edge," abut against an obstruction, or grade laterally into other layers. Original horizontality holds that sedimentary layers are originally formed horizontally and remain so unless deformed by subsequent processes.

Steno's writings were full of common sense. In superposition, he noted the most important criterion for relative age dating. In lateral continuity, he wrote about how correlation of sedimentary layers would be possible. In original horizontality, he noted the criterion necessary for any sort of analysis of later deformation, that is, the original state of a sedimentary layer can be assumed to be horizontal.

As insightful as Steno's writings were, there is no strong evidence that they were influential beyond the Renaissance era in which he lived. Later on, during the Enlightenment, naturalists like **James Hutton** (1726–1797), John Playfair (1748–1819), and **Charles Lyell** (1797–1875) apparently independently "re-discovered" the importance of these common-sense concepts and used them in their influential writings about geology and stratigraphy. Hutton, Playfair, Lyell, and others of their time wrote books and papers, which established the foundations of modern thought about stratigraphy. Their most important contributions included promoting the concepts of actualism (understanding the past by studying modern processes) and demonstrating such key concepts as stratigraphic correlation, predictable fossil succession, and the great antiquity of Earth.

The advancement of these key concepts were given a great boost by the pioneering work of the English field engineer **William Smith** (1769–1839), who compiled and published the first large-scale **geologic map** (Wales and southern England; 1815) employing modern concepts of stratigraphic correlation and fossil succession. Smith's success inspired others to this kind of work, and was particularly important in influencing the Geological Society of London (the first geological



The Grand Canyon in Arizona has exposed millions of years of strata, allowing geologists a glimpse back in Earth's history. ***National Park Service.***

organization; founded 1807) to embark upon its "stratigraphical enterprise" of research in the United Kingdom. The Society and the British Geological Survey (the first geological survey, founded 1835) were important promoters of early stratigraphic studies and venues for presentation of early research. Based upon these efforts, it is fair to assert that modern stratigraphy was born in the United Kingdom during this period.

In the nineteenth century, major efforts were made by British stratigraphers and their colleagues on the European continent to develop a unified stratigraphic succession (or "geological column") for rocks in their areas. Cambridge Professor Adam Sedgwick (1785–1873) and Scottish naturalist Roderick Murchison (1792–1871) became quite famous as the preeminent "system builders" of their time. Sedgwick studied and named the Cambrian System himself and with Murchison, the Devonian. Murchison studied and named the Silurian and Permian Systems by himself. There were others who did the same during the nineteenth century, thus establishing the basis of our modern geological time scale (which has periods of the same names as those given to "systems" of rock during an era when exact ages of rock strata were unknown). This was the birth of modern **chronostratigraphy**, which emphasizes subdivision of geological time by studying Earth's stratigraphic record.

A Swiss geologist, Amanz Gressley (1814–1865), studied Jurassic strata in **Europe** in hopes of understanding what happens to sedimentary layers where they grade into other layers. He recognized that lateral continuity of layers revealed many changes, which reflected different ancient environments. To this concept, he gave the name facies, meaning an aspect of a sedimentary formation. A German stratigrapher, **Johannes Walther** (1860–1937), took up Gressley's ideas in his own work and became more widely known than Gressley for work with sedimentary facies. To Walther, the facies represented primary characteristics of the rock that would help him understand how and where the rock formed. He used what he called the ontological method in facies stratigraphy, which he described whimsically as "... from being, we explain becoming." This was a direct application of actualism, advocated earlier by Hutton and others, but now applied in a time of enhanced understanding of the natural world. Walter was the first naturalist to spend large amounts of time in the field studying modern environments in order to better interpret the past. His two-volume work, *Modern Lithogenesis* (1983; 1984), was a watershed for modern research with sedimentary facies. Accordingly, Walter is regarded as the founder of modern facies stratigraphy. Although his work was not accepted well in the United States for many years (due, in part, to anti-German feelings during the early twentieth century), it later was studied extensively for its rich descriptions of modern sedimentary environments and ancient sedimentary facies. In the latter part of the twentieth century, facies stratigraphy became much more than an academic exercise when it was realized that such knowledge could help predict the occurrence of **petroleum** and certain ore minerals—and facilitate more productive extraction of these materials—in host **sedimentary rocks**.

At the outset of the twentieth century, Austrian stratigrapher Eduard Suess (1831–1914) became the first advocate of global changes of sea level and how those changes might relate to global stratigraphy. This concept, called eustatsy, holds that global sea level rises and falls during geological history lead to the great marine transgressions and regressions noted in many sedimentary strata from locales around the world. Suess called upon subsidence of the sea floor and displacement of seawater by sediment as reasons for this global effect (today we know that gain and loss of **polar ice** is another contributor to sea-level change). His work stimulated much research, and strongly influenced the well-known American geologist T.C. Chamberlain (1843–1928), who perpetuated these ideas through his many well-known papers on the subject. These ideas were important in the development of a modern concept in stratigraphy called sequence stratigraphy.

Sequence stratigraphy, which holds that large bodies of sedimentary strata are bounded by interregional **unconformities**, formed as a result of global eustatsy. In the early 1960s, sequence stratigraphy was put forth by the American stratigrapher L.L. Sloss (1913–1996) in a series of widely read papers. During the 1970s, Sloss's student, Peter Vail (1930–), formerly with Exxon Corporation (now Exxon-Mobil Corporation), further developed these concepts while studying seismic profiles of stratigraphy from the world's continental shelves. Vail's paper's established sequence stratigraphy as one of the main subdivisions of modern stratigraphy. To recognize their contributions, sequence stratigraphy is often referred to as Sloss-Vail sequence stratigraphy in their honor.

Vail's work spawned a huge effort to produce a highly detailed, eustatic sea-level cycle chart of Earth's history based upon the vast data collection at Exxon. His work was published in 1987 in the prestigious journal *Science*. Sequence stratigraphy and global sea-level cycle charts are concepts used today major petroleum-company exploration laboratories all over the world.

Today, facies stratigraphy and sequence stratigraphy are not the only types of stratigraphy practiced by geologists. Modern stratigraphy includes: lithostratigraphy (naming of formations for purposes of geological mapping); biostratigraphy (correlating rock layers based upon fossil content); chronostratigraphy (correlating rock layers based upon their similar ages); magnetostratigraphy (study and correlation of rock layers based upon their inherent magnetic character); **soil** stratigraphy (study and mapping of soil layers, modern and ancient); and event stratigraphy (study and correlation of catastrophic events in geological history). The latter may include global or regional layers formed by asteroid or comet impacts, major volcanic events, global **climate** or ocean-chemistry changes, and effects of slight changes in Earth's orbital parameters (e.g., **Milankovitch cycles**). Modern procedures and practices in stratigraphy are summarized in two widely read documents: the *North American Stratigraphic Code*, published by the American Association of Petroleum Geologists, and the *International Stratigraphic Guide*, 2nd edition, published by the Geological Society of America.

Because layered Earth materials possess so much information about Earth's past, including the entire fossil record—and a sedimentary record quite sensitive to atmospheric, climatic, and oceanic changes of the past—stratigraphy is the one subarea of geology entirely focused upon retrieving and understanding that record.

See also Correlation (geology); Geologic time; Historical geology; Marine transgression and marine regression; Unconformities

STRATOCUMULOUS CLOUD • *see* CLOUDS AND CLOUD TYPES

STRATOSPHERE AND STRATOPAUSE

The atmosphere of Earth can be divided into semi-horizontal layers or spheres, based on properties such as **temperature** variation, gas components, or electrical properties. While air pressure and air density always decrease with altitude in the atmosphere, it is not the case for temperature. Four temperature-varying layers of Earth's atmosphere can be distinguished: the **troposphere**, the stratosphere, the **mesosphere**, and the **thermosphere**. In the troposphere and the mesosphere, the temperature decreases with altitude, but in the stratosphere and thermosphere, the temperature increases with altitude (called temperature inversion). Between these layers, the temperature remains the same in the tropopause (between the troposphere and the stratosphere), the stratopause (separating the stratosphere and the mesosphere), and the mesopause (between the mesosphere and the thermosphere).

The stratosphere is the second lowest layer of Earth's atmosphere, located between the troposphere and mesosphere. The stratosphere and the mesosphere together are called the middle atmosphere. The stratosphere, which literally means the layered sphere, is located from about 12 miles (20 km) to 30 miles (50 km) altitude. About 99% of the total air mass of the atmosphere can be found in the bottom two layers, the troposphere and stratosphere. The stratosphere is not only less dense than the troposphere, but it also contains very dry air. The stratospheric temperature is warmer than the upper tropospheric temperature; the average temperature at the bottom of the stratosphere is around – 76°F (–60°C), and at the upper bound around –26°F (–3°C). The temperature increases with height in the stratosphere because of the thin, but highly concentrated, stratospheric ozone layer. It is located between 13 to 19 miles (20 to 30 km), and reaches its peak density at an altitude of about 16 miles (25 km).

Ozone is a special molecular form of **oxygen**, consisting of three oxygen atoms bonded together. It is created by incoming solar radiation, which breaks up ordinary molecular oxygen (O_2) into individual oxygen atoms, which can later combine with another ordinary oxygen molecule to form ozone (O_3). Because the ozone layer absorbs and scatters solar radiation, a form of energy, the stratosphere consequently warms up. Without the ozone layer life could not exist on Earth; ozone is the only atmospheric gas that protects the **biosphere** from the damaging effects of the sun's ultraviolet radiation. This is why the depletion of the ozone layer (ozone hole) caused by anthropogenic chlorofluorocarbons (CFCs) is a cause for scientific concern and study.

See also Atmospheric composition and structure; Ozone layer depletion; Troposphere and tropopause

STRATUS CLOUD • *see* CLOUDS AND CLOUD TYPES

STREAM CAPACITY AND COMPETENCE

Streams channel **water** downhill under the influence of **gravity**. Stream capacity is a measure of the total sediment (material other than water) a stream can carry. Stream competence reflects the ability of a stream to transport a particular size of particle (e.g., boulder, pebble, etc). With regard to calculation of stream capacity and competence, streams broadly include all channelized movement of water, including large movements of water in **rivers**.

Under normal circumstances, the major factor affecting stream capacity and stream competence is channel slope. Channel slope (also termed stream gradient) is measured as the difference in stream elevation divided by the linear distance between the two measuring points. The velocity of the flow of water is directly affected by channel slope, the greater the slope the greater the flow velocity. In turn, an increased velocity of water flow increases stream competence. The near level **delta** at the lower end of the Mississippi River is a result of low stream velocities and competence. In contrast, the Colorado River that courses down through the Grand **Canyon** (where the river drops approximately 10 ft per mile) has a high stream velocity that results in a high stream capacity and competence.

Channelization of water is another critical component affecting stream capacity and stream competence. If a stream narrows, the velocity increases. An overflow or broadening of a stream channel results in decreased stream velocities, capacity, and competence.

The amount of material (other than water) transported by a stream is described as the stream load. Stream load is directly proportional to stream velocity and stream gradient and relates the amount of material transported past a point during a specified time interval. The higher the velocity the greater the sum of the mass that can be transported by a stream (stream load). Components of stream load contributing to stream mass include the **suspended load**, dissolved load, and bed load. Broad, slow moving streams are highly depositional (low stream capacity) while high velocity streams have are capable of moving large rocks (high stream competence).

Alluvial fans form as streams channeling mountain **runoff** reach flatter (low, slope, low gradient) land at the base of the mountain. The stream loses capacity and a significant portion of the load can then settle out to form the alluvial fan.

The ultimate site of deposition of particular types and sizes of particles is a function of stream capacity and stream competence (along with settling velocity of particles). These factors combine to allow the formation of articulated sedimentary deposits of **gypsum**, **limestone**, **clay**, shale, siltstone, **sandstone**, and larger **rock** conglomerates. No matter how low the stream capacity, the solution load usually retains ions in solution until the water evaporates or the **temperature** of the water cools to allow **precipitation**.

In confined channels, stream competence can vary with seasonal runoff. A stream with low volume may only be able to transport ions, clays, and silt in its solution and suspension loads and transport **sand** as part of its **saltation** load. As stream flow increases the stream competence during seasonal flooding, the stream may gain the competence to move pebbles, cobbles, and boulders.

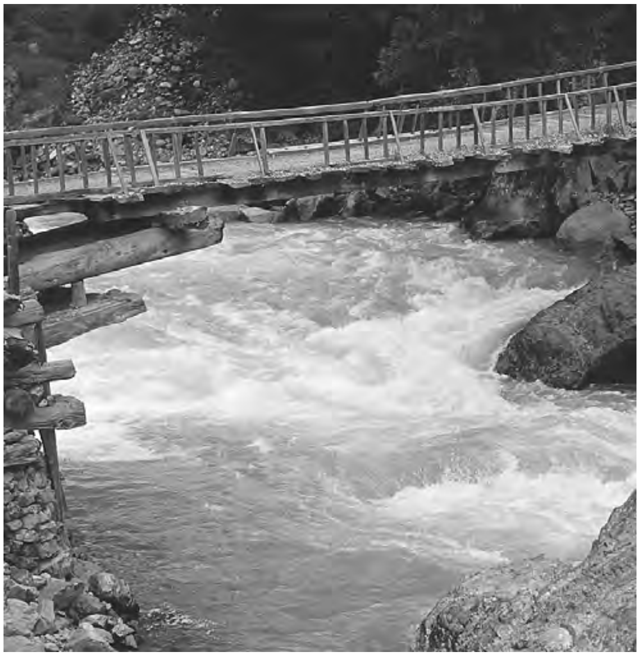
See also Bed or traction load; Bedforms (ripples and dunes); Channel patterns; Erosion; Estuary; Hydrogeology; Rapids and waterfalls; Sedimentary rocks; Stream valleys, channels, and floodplains

STREAM PIRACY

A stream can be defined as any flowing body of **water** in a clearly defined channel. Streams may increase the size of their valleys by the **erosion** of the **soil** and **rock** surrounding their channels, either by widening their valleys or by headward erosion. In the process of headward erosion, the stream valley at the uppermost part of the stream channel is worn away, and the stream channel is lengthened in the upstream direction. Because the sides of the uppermost part of the stream valley are often steeper than the sides of the valley further downstream, the lengthening of the stream channel usually proceeds faster than the process of valley widening. Rates of headward erosion and channel lengthening vary between different streams, because some streams will have steeper valleys, resulting in faster water flow rates and faster erosion. In some cases, this results in a phenomenon called stream piracy, in which part of the drainage of one stream is captured by another, faster-eroding stream.

A stream that has lost part of its drainage is termed beheaded. Stream piracy is also called stream capture or river capture.

See also Drainage basins and drainage patterns; Stream valleys, channels, and floodplains



Stream piracy is the result of the drainage of one stream being captured by another, faster-eroding stream. © *Roger Wood/Corbis. Reproduced by permission.*

STREAM VALLEYS, CHANNELS, AND FLOODPLAINS

Stream valleys, channels, and floodplains form complicated systems that evolve through time in response to changes in sediment supply, **precipitation**, land use, and rates of tectonic uplift affecting a drainage basin. Stream channels serve to convey flow during normal periods, whereas floodplains accommodate flow above the bankfull stage (**floods**) that occurs with frequencies inversely proportional to their magnitude. Bankfull stage is defined as the discharge at which the **water** level is at the top of the channel. Any further increase in discharge will cause the water to spill out of the channel and inundate the adjacent floodplain. Flood frequency studies of streams throughout the world show a remarkably consistent one to two-and-one-half year recurrence interval for bankfull discharge in most streams, averaging about one and a half years, meaning that small floods are relatively common events.

Stream channels are classified according to four basic variables: their slope or gradient (change in elevation per unit of distance along the stream channel), their width to depth ratio, their entrenchment ratio (flooplain width to bankfull width), and the predominant channel bed material (**bedrock**, gravel, cobble, **sand**, or **clay**). In general, the width of stream channels increases downstream more than the depth, so that large **rivers** such as the Mississippi may be 0.5 mi or more wide but less than 100 ft deep. Channels with large bed loads of coarse-grained materials, steep gradients, and banks composed of easily eroded sediments tend to be shallow and braided, meaning that flow occurs through many anastomosing channels separated by bars or islands. Streams with low gradients, small bed loads, and stable banks tend to meander in **space** and time, following a pattern that resembles an exaggerated sine wave. Another characteristic of streams with beds coarser than sand is the occurrence of riffle-pool sequences, in which the channel is segregated into alternating deep pools and shallow riffles. In steep mountain streams, the riffles can be replaced by steep steps over boulders or bedrock outcrops to form a step-pool sequence.

Stream channels can change in form over time as a function of **climate**, precipitation, sediment supply, tectonic activity, and land use changes. Increased precipitation or human activities—for example, heavy grazing or clear-cut logging—can lead to increased **erosion** or **mass wasting** that subsequently increase the amount of sediment delivered to streams. As a consequence, the channel and stream gradient change to accommodate the increased sediment load, which may in turn have adverse effects on aquatic habitat. For example, an influx of fine-grained sediment can clog the gravel beds in which salmon and trout spawn. The effect of urbanization is generally to increase storm **runoff** and the erosive power of streams because impervious areas (principally pavement and rooftops) decrease the amount of water that can infiltrate into the **soil**, while at the same time decreasing the amount of sediment that is available for erosion before runoff enters stream channels. Tectonic uplift can increase the rate of stream valley incision. Thus, stream channels represent the continually changing response of the stream system to changing conditions over geologic and human time spans.

Because streams are the products of continual change, many stream valleys contain one or more generations of stream terraces that represent alternating stages of sediment deposition (valley filling) and erosion (stream incision). Each flat terrace surface, or tread, is a former floodplain. Stream terraces can often be recognized by a stair-step pattern of relatively flat surfaces of increasing elevation flanking the channel; in many cases, however, stream terraces are subtle features that can be distinguished and interpreted only with difficulty.

Floodplains form an important part of a stream system and provide a mechanism to dissipate the effects of floods. When a stream exceeds bankfull discharge, floodwater will begin to spill out onto the adjacent flat areas where its depth and velocity decrease significantly, causing sediment to fall out of suspension. The construction of flood control structures such as artificial levies has allowed development on many floodplains that would otherwise be subjected to regular inundation. Artificial levies, however, also increase the severity of less frequent large floods that would have been buffered by functioning floodplains, and can thereby provide a false sense of security. Current trends in flood hazard mitigation are therefore shifting away from the construction of containment structures and towards more enlightened land use practices such as the use of floodplains for parks or green belts rather than residential development.

See also Bed or traction load; Bedforms (ripples and dunes); Canyon; Channel patterns; Drainage basins and drainage patterns; Drainage calculations and engineering; Hydrologic cycle; Landscape evolution; Sedimentation; Stream capacity and competence

STRIKE AND DIP

Geologists use a prescribed method of determining the attitude (or orientation in three-dimensional **space**) of **rock** layers or any other planar geological feature (e.g., metamorphic foliation, fractures, faults, and tops of tabular units like formations). The method involves measurement of strike and dip of the rock layers or planar features. Strike is defined as the compass direction, relative to north, of the line formed by the intersection of a rock layer or other planar feature with an imaginary horizontal plane. The intersection of two flat planes is a straight line, and in this instance, the line is geologic strike. According to convention, the compass direction (or bearing) of this line is always measured and referred to relative to north. A typical bearing is given, for example, as N 45° E, which is a shorthand notation for a bearing that is 45 degrees east of north (or half way between due north and due east). The only exception to this north rule occurs where strike is exactly east-west. Then, and only then, is a strike direction written that is not relative to north.

Dip, as a part of the measurement of the attitude of a layer or planar feature, has two components: dip direction and dip magnitude. Dip direction is the compass direction (bearing) of maximum inclination of the layer or planar feature down from the horizontal. If a **marble** is held anywhere along the strike line on a layer or planar feature and then is released, thus allowing it to roll down the layer or planar feature, the marble would roll along a line showing true dip direction. This true dip direction is always perpendicular (i.e., at a 90 degree angle) to strike. Dip magnitude is the smaller of the two angles formed by the intersection of the dipping layer or planar feature and the imaginary horizontal plane. However, dip magnitude can also be equal to either zero or 90 degrees, where the layer or planar feature is horizontal or vertical, respectively.

A specially designed instrument, called a Brunton pocket transit, is used by geologists to measure strike, dip direction, and dip magnitude in the field. A Brunton pocket transit has a compass, bubble level (for finding horizontal), and a dip-angle measuring device (clinometer) built into it. Information on strike and dip obtained using the Brunton is then conveyed to a **geologic map** and plotted there using a strike and dip symbol. This symbol, about the length of the word *the* on this page, consists of a long bar oriented parallel to strike and a short spike perpendicular to the long bar showing the bearing of true dip direction. A small number printed by the symbol indicates the actual dip magnitude in degrees. On some maps, this number is not printed or is not printed by all such symbols.

Measurement of strike and dip (i.e., the attitude of rock layers or other planar geologic features) helps geologists construct accurate geologic maps and geologic cross-sections. For example, data on rock attitudes helps delineate fold structures in layered rocks. Attitude of other geologic structures like faults can be understood using strike and dip as well. It is especially critical to understanding geologic relations among rock bodies in the subsurface realm that surficial (relating to the surface) strike and dip of rocks is well known.

For entirely subsurface studies of strike and dip, devices called dip-meter tools can be lowered into drill holes. These tools, which use electrical properties of rocks in the well wall to sense attitude, help delineate subsurface orientations of rock layers and other planar features. Information from such subsurface studies is critical in areas where surficial attitude measurements are not adequate to understand subsurface structures. All surface and subsurface information on attitudes of rocks is important in helping geologists understand the structure and origin of Earth's **crust**.

See also Faults and fractures; Folds; Orientation of strata

STYLOLITES • *see* MARBLE

SUBDUCTION ZONE

Subduction zones occur at collision boundaries where at least one of the colliding **lithospheric plates** contains oceanic **crust**. In accord with plate tectonic theory, collision boundaries are sites where lithospheric plates move together and the resulting compression causes either subduction (where one or both lithospheric plates are driven down and destroyed in the molten mantle) or crustal uplifting that results in **orogeny** (mountain building). Subduction zones are usually active **earthquake** zones. Subduction zones are the only sites of deep earthquakes. The areas of deep earthquakes, ranging to a depth of 415 mi (670 km), are termed Benioff zones. Deep earthquakes occur because of forces due to plate drag and mineral phase transitions. The release of forces due to sudden slippage of plates during subduction can be quick and violent. Subduction zones can also experience shallow and intermediate depth earthquakes.

Oceanic crust is denser than continental crust and is subductable. Moreover, as oceanic crust–bearing plates move away from their site of origin (divergent boundaries), the oceanic crust. The cooling results in an increase in general density of the oceanic crust. The concurrent loss of buoyancy makes it easier to subduct the crust. In addition, colliding plates create tremendous force. Although lithospheric plates move very slowly, the plates have tremendous mass. Accordingly, at collision each lithospheric plate carries tremendous momentum (the mathematical product of velocity and mass) that provides the energy to drive subduction. In zones of convergence, including subduction zones, compressional forces (i.e., compression of lithospheric plate material) dominates.

Earth's crust is fractured into approximately 20 lithospheric plates. Lithospheric plates move on top of the asthenosphere (the outer plastically deforming region of Earth's mantle). Because Earth's diameter remains constant, there is no net creation or destruction of lithospheric plates. Each lithospheric plate is composed of a layer of oceanic crust or continental crust superficial to an outer layer of the mantle. Oceanic crust is composed of high-density rocks, such as **olivine** and **basalt**. In contrast, continental crust is composed of lower density rocks such as **granite** and **andesite**.

Within subducting zones, oceanic crust can make material contributions of lighter crustal materials to overriding continental crust. As the oceanic crust subducts, parts may be scraped off to form an accretion prism. Rising material at sites where oceanic crust subducts may form **island arcs**.

When oceanic crust collides with oceanic crust, both subduct to form an oceanic trench (e.g., the Marianas trench). Dual plate subduction can result in **ocean trenches** with depths approximating 38,000 ft.

When oceanic crust collides with continental crust, the oceanic crust subducts under the lighter continental crust. The subducting oceanic crust pushes the continental crust upward into **mountain chains** (e.g., the Andes) and may contribute lighter molten materials to the overriding continental crust to form volcanic arcs (e.g., the “ring of fire”; a ring of volcanoes bordering the Pacific Rim. Because continental crust does not subduct, when continental crust collides with continental crust, there is a uplift of both crusts.

At triple points where three plates converge, the situation becomes more complex and in some cases there is a mixture of subduction and uplifting.

Convergent plate boundaries are, of course, three-dimensional. Because Earth is an oblate sphere, lithospheric plates are not flat, but are curved and fractured into curved sections akin to the peeled sections of an orange. Convergent movement of lithospheric plates can best be conceptualized by the movement together of those peeled sections over a curved surface.

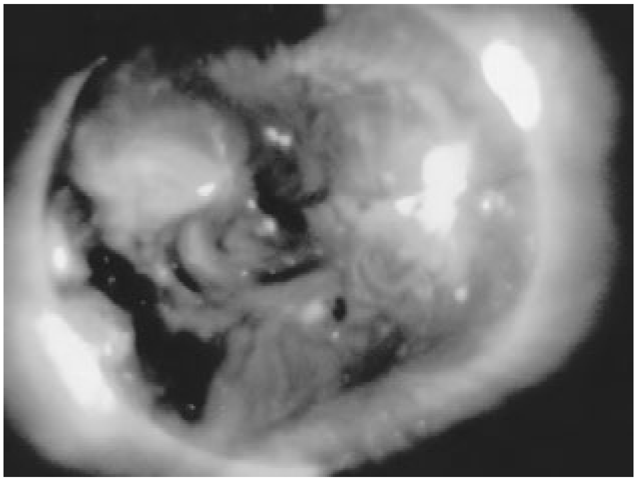
See also Divergent plate boundary; Earth, interior structure; Earthquakes; Geologic time; Magma chamber; Magma; Mohorovicic discontinuity (Moho); Plate tectonics; Volcanic eruptions; Volcano

SUBLIMATION OF GLACIERS • *see* GLACIATION

SUN (STELLAR STRUCTURE)

The Sun is the star about which Earth revolves. A typical star, Earth’s sun is composed of gases and heavier elements compressed to enormous density and heated to levels that sustain **nuclear fusion** (the transformation of hydrogen into helium and heavier elements). The Sun consists of an inner core surrounded by a radiative zone and then a convective zone. The surface of the Sun is termed the photosphere. Surrounding the Sun is a solar corona—an atmosphere of hot plasma, gases, and outflowing particles.

Nuclear fusion take place in the Sun’s core and it is in this region that the bulk of the Sun’s production of energy, heat, and gamma rays takes place. The radiative zone surrounding the core is of such high density that photons generated in the core can take millions of years to pass through to the surrounding radiative zone. Undergoing an enormous number of collisions, absorptions and regenerations, photons span a spectrum frequencies that correspond to gamma rays, x ray, ultraviolet light, visible light, infrared light, microwaves, and radio waves. Photon passage through the convective zone provides energy to drive massive convective currents of hot gas.



X-ray photograph of the solar corona. ***U.S. National Aeronautics and Space Administration (NASA).***

The photosphere is the visible outer or surface layer of Sun. At the photosphere, solar temperatures cool to about 5800 K. The photosphere often features sunspots (areas of surface relatively cooler due to differential temperatures in convective currents). Sunspots occur in cycles with maximum activity peaking every 11 years.

Largely composed of gas, the Sun exhibits differential **rotation** speeds that depend on solar **latitude**. The rotational period varies from approximately 25 days at the equator to 29 days near the polar regions.

The chromosphere surrounds the photosphere and extends thousands of miles. Temperatures increase in the chromosphere and range up to 1,000,000 K. The chromosphere is part of the solar corona that extends millions of miles into **space**. Influenced by turbulent magnetic fields coronal temperatures range up to 3,500,000 K. At these high temperatures, electrons are stripped from gases and plasma streams form a solar **wind**. The solar chromosphere and corona are usually visible only when an **eclipse** blocks the photosphere.

Solar flares and prominences, flame-like eruptions of hot gas, sometimes extend into the chromosphere and corona.

British astronomer Fred Hoyle once described the evolution of a star—including, of course, the Sun—as a continual war between nuclear **physics** and **gravity**.

The gravity of the stellar material pulls on all the other stellar material striving to bring about a collapse. However, the gravitational compression is opposed by the internal pressure of the stellar gas that normally results from heat produced by nuclear reactions. This balance between the forces of gravity and the pressure forces forms an equilibrium, and the balance must be exact or the star will quickly respond by expanding or contracting in size. So powerful are the separate forces of gravity and pressure that should such an imbalance occur in the Sun, it would be resolved within hours. That fact that Earth's sun is about 5 billion years old emphasizes just how exactly and continuously that balance is maintained.

In addition to its reliance on balance between gravity and pressure, the internal structure of a sun depends on the behavior of the stellar material itself. Most stars are made primarily of hydrogen, the dominant form of matter in the universe. However, the behavior of hydrogen will depend on the **temperature**, pressure, and density of the gas. Indeed, the quantities temperature, pressure, and density are known as state variables, because they describe the intrinsic state of the material. Any equation or expression that provides a relationship between these variables is called an equation of state.

Most of the energy that flows (i.e., undergoes a series of transformations) from a star originates at its center. The way in which this energy flows to the surface will also influence the internal structure of the star.

There are three ways by which energy flows outward through a star. They are conduction, convection, and radiation.

However, the more opaque the material is, the slower the convectional and radiative transfers of heat and energy (e.g. electromagnetic radiation or "light") flow of energy will be. In the Sun, where light flowing out from in the core will travel less than a centimeter before it is absorbed, it may take a million years for the light energy to make its way to the surface.

The mode of energy transport, equations of state, and equilibrium equations can be quantified and self-consistent solutions found numerically for stars of given mass, composition and age. Such solutions provide model stellar interiors, and supply the detailed internal structure of a particular star. For the vast majority of stars that derive their energy from the nuclear fusion of hydrogen into helium, the internal structure is quite similar. Such stars are termed main sequence stars and are located in a band on a Hertzsprung-Russell diagram (developed independently between 1911–13 by Danish astronomer Ejnar Hertzsprung (1873–1967) and American astronomer Henry Norris Russell (1877–1957).

The Sun is a main sequence star. The Sun's core is surrounded by a churning convective envelope that carries the energy to within a few thousand kilometers of the surface, where energy again flows primarily by radiation as it escapes into space. This structure is common to all main sequence stars with mass less than 1.5 times the mass of the Sun.

Changes to the stellar structure over time are described by the theory of **stellar evolution**.

See also Big Bang theory; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Solar energy; Solar illumination: Seasonal and diurnal patterns; Solar sunspot cycles; Solar system; Stellar life cycle

SUNSPOTS • *see* SOLAR SUNSPOT CYCLE

SUPERCONTINENTS

The earth comprises a number of **lithospheric plates** that move apart at mid-oceanic ridges, are consumed at subduction zones, collide with each other in collisional orogens, or slide past each other along transform boundaries. Although oceanic **crust** is continually being created and destroyed, long-lived stable parts of continents called cratons have remained undeformed for billions of years. Continental plates containing ancient cratons have episodically collided and assembled in global periods of orogenesis to form supercontinents. Supercontinents eventually become unstable, as such a large single landmass acts as a thermal lid, limiting escape of Earth's internal heat. Supercontinent breakup occurs when old crustal weaknesses (such as orogenic belts created during supercontinent assembly) overlay several **mantle plumes**, or due to the formation of a superplume. Dispersed fragments move across the globe to subsequently amalgamate to form another supercontinent. The process of supercontinent formation, breakup, and dispersal has continued cyclically through Earth's history.

Plate reconstructions for periods younger than 180 million years (the oldest age of crust in present-day **oceans**) can be made by graphically undoing seafloor spreading magnetic anomalies of known age. Offshore **gravity**, calculated from **satellite** altimetery of the sea surface, defines continental margins and structures in oceanic crust that can also be used in recent continental reconstructions. **Rotation** poles (Euler poles), about which lithospheric plates are displaced, can be determined from **transform faults** interpreted from satellite altimeter-derived images. All reconstructions are based on the generally held view that Earth has maintained a constant radius (although this is questioned by some who contend that the earth has progressively expanded). For older periods, scientists rely on the following to establish, or at least infer, continental correlations:

- Linking of orogenic belts and intracratonic structures (e.g., major **shear zones** of the same age and displacement sense)—accurate dating is unfortunately lacking from many **Precambrian** terrains, hindering such correlations. Regional aeromagnetic data is valuable in comparing lithological trends and structural elements as basement rocks below superficial cover and sedimentary basins are imaged. Regional gravity data highlights major crustal structures.
- Mafic dikes—dike swarms (readily discernable on aeromagnetic images) may be traced from one **craton** to another. Dikes may converge on an **area** above the center of a former mantle plume.
- Common **rock** types, ages, and fossil assemblages in **sedimentary rocks** on conjugate margins—provenance studies and ages of detrital zircons for sedimentary basins provide information concerning the source terrains for sedimentary basins. Sedimentary source rocks absent from the craton the basin is situated in may be found on previously contiguous continents.
- Paleomagnetism and polar wander paths—when sedimentary rocks are deposited or when igneous or meta-

morphic rocks cool below 578° for magnetite and 675° for hematite (the minerals' Curie temperatures), these iron-rich **minerals** preserve the orientation of the earth's **magnetic field**. Rocks of the same age from joined continents exhibit a common magnetic pole. Apparent polar wander paths linking poles of different ages graphically portray the displacement of a continent with time. Changes in previously overlapping apparent polar wander paths for two continents indicate the time continents rifted apart.

- Large igneous provinces of the same age and with characteristic geochemical signatures (representing portions of the same igneous province prior to breakup)—Archean to late Mesoproterozoic correlations are, however, highly problematic due to the poor to non-existent paleomagnetic database, the wide dispersal of cratons following their breakup and the likely disruption or tilting of old cratons during reworking along craton margins.

An **Archean**, 3.1 (to possibly even 3.6) billion years old supercontinent Vaalbara, in which the South African Kaapvaal Craton was joined to the Pilbara Craton of Western **Australia**, is the oldest proposed supercontinent. The concept of Vaalbara is based on similarities in sedimentary sequences on both cratons. The existence of Vaalbara has, however, been questioned due to differences in magmatic events between both cratons, and the possibility for similar sedimentary successions to have been deposited on separate continents due to global sea level changes. Recent paleomagnetic evidence suggests that the cratons were not contiguous about 2.8 billion years ago.

Another Archean to Paleoproterozoic supercontinent, Ur (the German word for original) has been proposed. Ur is thought to comprise a nucleus of the Kaapvaal and Pilbara cratons (although not adjacent to each other as in Vaalbara), the Indian Bhandara and Singhbhum cratons, and possibly some Archean East Antarctic terrains. A 1.8 to 1.5 billion year supercontinent Columbia comprising most continents then existing on Earth has also been proposed in which eastern India, Australia, and their contiguous portion of East **Antarctica** was joined to western **North America**.

Rodinia (from the Russian *rodit,* meaning to grow) is the late Mesoproterozoic to late Neoproterozoic (approximately 1,200 to 700 million year) supercontinent formed by the assembly of Precambrian terrains of Australia, North America-Canada, India, Madagscar, Sri Lanka, and East Antarctica. The idea for such a supercontinent initially came from the recognition of geological similarities between western Canada and southeastern Australia, and likely links between 1.3 to 0.9 billion-year-old orogenic belts. The term Grenvillian belts has been loosely used to encompass orogens formed during this broad time span. This is, however, not the strict definition of the Grenvillian **Orogeny**, which is defined as occurring between 1,090 and 980 million years ago in its type area, the Grenville Province of North America. There is still much debate as to the configuration of continents within Rodinia.

In the first SWEAT (from *S*outh*w*estern United States–*E*ast *Ant*arctica) configuration, Laurentia is positioned such that western Canada is opposite eastern Australia. Grenvillian orogens (such as the Central Indian Tectonic Zone and Pinjarra Orogen of Western Australia) that were not part of a continuous orogenic belt were omitted in this reconstruction, giving it a somewhat false simplicity. In a modified version, South China (formed through collision of the Cathaysia and Yangtze blocks) is positioned between Australia and Laurentia. In another reconstruction for Rodinia, AUSWUS (*Aus*tralia–*W*estern *U*nited *S*tates), eastern Australia is attached to the western United States. Both are compatible with available paleomagnetic data for 1,140 million years; however, both are not compatible with recent paleomagnetic poles for 1,070 million-year-old rocks from Laurentia and Western Australia. In an attempt to explain these poles, a reconstruction of Rodinia called AUSMEX (*Aus*tralia–*Mex*ico) has Laurentia in a rotated position with respect to Australia, with the Grenville Province of North America continuing directly into northeastern and central Australia. In the SWEAT and AUSWUS reconstructions, northeastern India joins with southwestern Australia, and southeastern India is linked to Antarctica. Despite sound geological links between Proterozoic orogenic belts supporting this configuration, current paleomagnetic data suggest that India and part of East Antarctica may not have amalgamated with Australia until 680 to 610 million years ago. Clearly, there are still many problems to be resolved before consensus is reached for a reconstruction of Rodinia compatible with all available data. It must also be asked whether palaeomagnetic data alone is a reliable means of establishing ancient positions of continents.

Rodinia split into two main fragments approximately 750 million years ago. Pannotia (meaning all southern) is the name given to a supercontinent formed when the northern block (comprising Australia, Antarctica, India, Madagascar, Arabia, and parts of China), Laurentia, and cratonic blocks in East **Africa**, Mozambique, Madagascar, and **South America** were amalgamated through collision in the Pan-African orogeny. Pannotia broke up into Laurentia, Baltica, Siberia, and Gondwanaland at the end of the Precambrian, about 590 million years ago.

The idea of links between India, central and southern Africa, and Madagascar based on the common occurrence of *glossopteris* (a fossilized seed fern first described in early Permian **coal** seams in central India) and other fossil assemblages was first proposed in 1885 by the Austrian geologist Eduard Suess. Suess coined the term Gondwanaland, meaning the land of the kingdom of the Gons (a Dravidian people in central India) for the area he thought to have been linked by land bridges between fixed continents. Australia and Antarctica were subsequently added following further *glossopteris* discoveries. The proposition of links between continents predated the concepts of continental drift and **plate tectonics**, but was subsequently used as evidence in their formulation. Gondwanaland continents contain similar Permo-Carboniferous (286 million year old) to late Jurassic–early Cretaceous (100 million year) sedimentary successions. Permo-Carboniferous tillites and other similar glacial deposits in India, Australia, and Antarctica are the vestiges of a large **ice** sheet. Older ice sheets were present in Africa and South America. Early reconstructions of Gondwanaland were based on the outlines of continents, structural features, and broad matches in **geology**. These have been subsequently refined using paleomagnetic and seafloor spreading data.

Gondwanaland was separated by the Tethys Ocean from another supercontinent, Laurasia, formed through collision of Laurentia (North America), Baltica (Scandinavian continents), parts of **Europe**, and Siberia approximately 400 million years ago. The supercontinent Pangaea (meaning all Earth) was formed by the collision of Laurasia with Gondwanaland approximately 275 million years ago following closure of part of the Tethys, and the collision with Cimmeria (fragments of Turkey, Afghanistan, Iran, Tibet, and Indochina). Mountain belts such as the Appalachians and Urals were formed in this event. The breakup of Pangaea in the Late Jurassic to Early Cretaceous occurred largely due to **rifting** along old weaknesses when they became aligned between mantle plumes.

Understanding the configurations of past supercontinents is of more than academic interest. The formation and dispersal of supercontinents has had a marked effect on past changes in **ocean circulation** patterns and hence on Earth's **climate**. Major mineral provinces on one continent may have as yet undiscovered corollaries on another, once adjacent continent. Placer gold deposits in a sedimentary basin on one continent may have been eroded from vein or shear zone hosted deposits on another continent. The Mt. Isa Belt in Queensland, Australia, is truncated by a rifted margin formed during the breakup of Rodinia. Rich gold and base metal deposits may exist in its continuation on another, yet undefined terrain, possibly within southeast China or North America (placed against Queensland in various Rodinia reconstructions).

See also Continental drift theory; Earth, interior structure; Earth (planet); Geologic time

SUPERIMPOSED STREAMS • *see* DRAINAGE BASINS AND DRAINAGE PATTERNS

SUPERPOSITION

Originally observed by Nicholas Steno in the seventeenth century, the law of superposition states that in an undisturbed series of **sedimentary rocks**, the oldest rocks will be at the bottom and the youngest will be at the top. Before the development of radiometric dating techniques, the law of superposition was used to assign relative ages to **rock** units based on their position in the sequence. For example, looking at a series of undeformed sedimentary rocks one could assume that the rocks, and therefore associated **fossils**, of the top layers were younger than those below. This idea builds on one of Steno's other observations, the law of original horizontality, which states that sedimentary layers are approximately horizontal when deposited. It follows that any body of rock that cuts across the sequence must be younger than all of the layers that it cuts.

If a sequence of sedimentary rocks has been deformed, the law of superposition may be difficult to apply. If a sequence of beds has been tilted, it should be clear that the law of superposition cannot be applied until the original up direction is verified. Overturned beds cause a similar problem, and relative ages may be calculated incorrectly if the deformation is not noticed. There are several younging indicators to aid in determination of the original up direction. These include mudcracks, cross beds, graded **bedding**, load and flute casts, and burrow marks. Once younging direction has been determined, the law of superposition may be applied even to a deformed sedimentary sequence.

See also Bedforms (ripples and dunes); Cross cutting; Lithification; Stratigraphy

SURF ZONE

The surf zone is one of the most dynamic regions of the marine environment. Not only is it highly energetic, it also supports a wide diversity of life forms. Surf zones in both sandy and rocky shores produce dynamic surroundings that shape the entire coastal region.

Waves are initiated at sea where winds sweep across the surface of the **water**. Some of the energy of the **wind** is transferred to the surface and small sinusoidal waves appear on top of the water. The wave often increases in energy with added winds. The height of oceanic waves is dependant on the energy of the wind which may be quite high during storm events.

The waves continue until they reach the shore. Once there, they strike the shore and lose their energy. What happens during this process is of great importance to geologists and those who live near the beach.

Ocean waves are very interesting examples of wave **physics** found in nature. A look at the wave in cross-section appears as a series of linked "S" shapes. The high point of the individual curve is called the crest. The low point is the trough. The size of the individual waves (the amplitude) and the frequency (the rate at which a series of waves pass a particular point during a specific amount of time) are determined by the amount of energy a group of waves contains.

The long waves strike the shore at an angle. Waves will rarely, if at all, touch the shore at a parallel line to the shore. This is a result of the changing **topography** of the land. When the wave strikes the shore it is refracted and a great deal of its energy is directed at an oblique angle to the original wave. This increases the energy of the wave effect and, for anyone who has experienced it, produces a significant push-pull type of action. Being caught in this **area**, named the swash, can be dangerous under certain conditions such as rip **tides** formation.

Geologists are concerned about the region where waves break on the shore. Small circular currents occur in the water that produce the characteristic swell shape. As these circular currents reach the shore and strike the bottom, they are compressed. This compression eventually breaks down the wave structure and the water spills over on itself at the crest. This is the point at which waves are commonly called "breakers." The bottom sediments act as a further drag on the wave and deplete it of much of its energy. Any sediments that were initially captured by the breaking wave are dumped and moved onto the beach. At the same time, the refracted wave captures sediment and pulls it back down the shoreline. This repeated motion causes **sand** grains to migrate down the beach as waves strike again and again. Where the shore is rocky, the force of the waves wears away the rocks and transports smaller clasts (sedimentary particles) out to sea and the coast. This type of **erosion** is a major physical process that sculpts cliffs around the world. The entire area of breaking waves, including the slopeface of the land, is called the surf zone.

See also Beach and shoreline dynamics; Dunes; Sedimentation; Wave motions

SURVEYING INSTRUMENTS

Surveying is the apportionment of land by measuring and mapping. It is employed to determine boundaries and property lines, and to plan construction projects. Surveying instruments are designed to precise (repeatable) and accurate apportionment measurements.

Throughout history, civilizations with high levels of sophistication in construction methods required surveys to ensure that work came out according to plan. Formal surveying on a large scale is thought to have originated in ancient Egypt as early as 2700 B.C., with the construction of the Great Pyramid of Khufu at Giza, though the first recorded evidence of boundary surveying dates from 1400 B.C. in the Nile River valley.

The Roman Empire relied heavily on surveying. In order to forge an empire that stretched from the Scottish border to the Persian Gulf, a large system of roads, bridges, aqueducts, and canals was built, binding the country economically and militarily. Surveying was a major part of Roman public works projects. It also was used to divide the land among the citizens. Roman land surveying was referred to as *centuriation*, which was a common rectangular unit of land **area**. These land parcels can still be seen in aerial photographs taken over France and other parts of Europe—the work of the Roman *agrimensores*, or measurers of land. The property lines were usually marked by stone walls and boundary markers.

Consistent with the rise of trigonometry and calculus, new surveying instruments emerged. The theodolite was invented in the sixteenth century. Its precise origin is unclear, but one version was invented by English mathematician Leonard Digges in 1571, who gave it its name. An improved theodolite was invented by Jesse Ramsden more than 200 years later in 1787. Its use led to the establishment of the British Ordnance Survey.

Made up of a **telescope** mounted on a compass or of a quadrant plus a circle and a compass, the theodolite is used to measure horizontal and vertical angles. The modern theodolite is usually equipped with a micrometer, which gives magnified readings up to 1/3600°, or one second of arc. The micrometer is derived from the vernier scale, which was invented by French engineer and soldier Pierre Vernier (1584-1638) in 1631 to measure in fractions.

The transit is a theodolite capable of measuring horizontal and vertical angles, as well as prolonging a straight line or determining a level sight line. A telescope atop a tripod assembly is clamped in position to measure either horizontal or vertical angles. The transit employs a plumb bob hanging from the center of the tripod to mark the exact location of the surveyor.

The practice of triangulation was introduced by Gemma Frisius in 1533. By measuring the distance of two sides of a triangle in a ground survey, the third side and the triangle's area can be calculated. Triangulation was aided by the inventions of the prismatic **astrolabe** and the heliotrope. The latter was invented by German mathematician Johann Gauss (1777-1855), who is considered the father of geodesy, the science of Earth measurement. Both instruments used a beam of sunlight to signal the positions of distant participants in a land survey.

Other survey instruments include the surveyor's compass, which is used for less precise surveying. The surveyor's level is used to measure heights of points above sea level or above local base points. Metal tapes, first introduced by English mathematician Edmund Gunter in 1620, are used for shorter measurements.

In the late twentieth century, surveying has been aided greatly by **remote sensing**: Photogrammetry employs aerial photography to survey large areas for topographic mapping and land assessment purposes, **satellite** imagery has increased the aerial coverage of surveys, and laser technology has increased the precision of survey sightings.

See also Cartography; Geologic map; Petroleum detection; Topography and topographic maps

SUSPENDED LOAD

Suspended load consists of sediment particles that are mechanically transported by suspension within a stream or river. This is in contrast to **bed or traction load**, which consists of particles that are moved along the bed of a stream, and dissolved load, which consists of material that has been dissolved in the stream **water**. In most streams, the suspended load is composed primarily of silt and **clay** size particles. Sand-size particles can also be part of the suspended load if the stream flow velocity and turbulence are great enough to hold them in suspension.

The suspended load can consist of particles that are intermittently lifted into suspension from the stream bed and of wash load, which remains continuously suspended unless there is a significant decrease in stream flow velocity. Wash load particles are finer than those along the stream bed, and therefore must be supplied by bank **erosion**, **mass wasting**, and mass transport of sediment from adjacent watersheds into the stream during rainstorms.

Water density is proportional to the amount of suspended load being carried. Muddy water high in suspended sediment will therefore increase the particle buoyancy and reduce the critical shear stress required to move the bed load of the stream.

The ratio of suspended load to bed load in a stream depends on the ratio of the shear velocity (a property of the flowing water that reflects the degree of turbulence) and the fall velocity (a property of the sediment grains). The fall velocity is that at which a sediment particle will fall through still water, and thus depends on both grain size and **mineralogy** (density). Bed-load transport predominates when the shear velocity is significantly less than half the fall velocity and suspended load transport predominates when the shear velocity is two to three times greater than the fall velocity. Mixed-mode transport occurs when the ratio falls within a range of approximately 0.4 to 2.5.

See also Erosion; Rivers; Sedimentation; Stream valleys, channels, and floodplains

SYNCLINE AND ANTICLINE

Syncline and anticline are terms used to describe **folds** based on the relative ages of folded **rock** layers. A syncline is a fold in which the youngest rocks occur in the core of a fold (i.e., closest to the fold axis), whereas the oldest rocks occur in the core of an anticline.

It is important to note that syncline and anticline do not necessarily relate to the shape or orientation of folded layers, although the origin of the words implies this. The term originates from the Greek word *sun (xun)*, meaning together, and the Greek word *klei*, meaning to lean, so syncline implies leaning together or leaning towards. *Ant* is the Greek prefix meaning opposite or opposing, so the word anticline implies oppositely leaning. Beds **dip** towards the fold axis in a syncline and away from the fold axis in an anticline only when the folded layers were upright before folding (i.e., where younger layers overlaid older layers). Before describing folds, it is therefore necessary to establish the primary order in which layers were deposited. To do this, facing, younging, or way-up criteria are used. These are synonymous terms for primary sedimentary structures (e.g., graded or cross-bedding) or igneous structures (e.g., vesicles, pillows) preserved in the folded layers. Where the relative ages of rocks are not known (as is often the case in metamorphic rocks), the term synform and not syncline should be used to describe folds where layers are bent downwards so that they dip towards the fold axis, and antiform and not anticline should be used where beds are arched upwards so that layers dip away from the fold axis.

Where rock layers have been inverted prior to folding, such as by folding about a larger fold with a shallowly inclined axial surface, the oldest rocks now occur in the core of folds where layers dip towards the fold axis. Such folds are called synformal anticlines; synformal because of their shape and anticline because of the relative ages of folded layers. The youngest layers in an overturned sequence occur in the core of folds called antiformal synclines where layers dip away from the fold axis.

T

TALUS PILE OR TALUS SLOPE

Geologists define talus as the pile of rocks that accumulates at the base of a cliff, chute, or slope. The formation of a talus slope results from the talus accumulation.

Because the term "talus" incorporates the concept of a pile, many geologists prefer it to "talus pile" and reserve the term "talus slope" for specific reference to the surface of the talus.

The recognition and characterization of talus slopes is often important in determining the potential for mass movements (landslides, etc.). Movements occur whenever the talus slope exceeds the critical angle. The exact angle at which failure takes place depends upon the materials (e.g., **rock** type), rock size, moisture content, but dry homogenous materials in a pile generally experience slope failure when the angle of repose (the resting slope angle) exceeds 33–37°. The critical angle lowers as materials become less intrinsically cohesive or when friction between particles is reduced by rain or other forms of moisture. Moisture also adds to the overall mass of the slope and thus increases the gravitational force on the slope.

For example, if a cliff or rock formation is composed of shale, the processes of **weathering** and the force of **gravity** (a shear stress) allow the downslope accumulation of shale rock fragments and debris at the base of the formation. The talus slope is triangular, with the internal angles of the sides of the triangle (the slope's angle of repose) limited by the critical angle.

The degree of sameness in size, layering, and homogeny of the talus is referred to as sorting. As a general rule, talus accumulated from rockfalls is better sorted than talus created by glacial deposits but far less sorted than piles constructed by **sedimentation**. Contributing rock that is irregularly fractured does not **weather** evenly and because it breaks off in large irregular pieces, contributes to a poorly sorted talus slope.

See also Landscape evolution; Landslide; Mass movement; Mass wasting

The formation of a talus slope results from the talus accumulation.
© Jack Dermid. Reproduced by permission.

TECTOSILICATES

The most abundant rock-forming **minerals** in the **crust** of Earth are the silicates. They are formed primarily of **silicon** and **oxygen**, together with various **metals**. The fundamental unit of these minerals is the silicon-oxygen tetrahedron. These tetrahedra have a pyramidal shape, with a relatively small, positively charged silicon cation (Si^{+4}) in the center and four larger, negatively charged oxygen anions (O^{-2}) at the corners, producing a net charge of –4. **Aluminum** cations (Al^{+3}) may substitute for silicon, and various anions such as hydroxyl (OH^{-}) or fluorine (F^{-}) may substitute for oxygen. In order to form stable minerals, the charges that exist between tetrahedra must be neutralized. This can be accomplished by the sharing of oxygen cations between tetrahedra, or by the binding together of adjacent tetrahedra with various metal cations. This in turn creates characteristic silicate structures that can be used to classify silicate minerals into **cyclosilicates**, **inosilicates**, **nesosilicates**, **phyllosilicates**, **sorosilicates**, and tectosilicates.

Silicon-oxygen tetrahedra form a three-dimensional framework in the tectosilicates, and minerals of this type comprise about 64% of Earth's crust. In addition, the tectosilicate minerals known as the feldspars are the most abundant group of the rock-forming silicates. Feldspars include the alkali feldspars microcline and orthoclase, both of which have the same chemical formula ($KAlSi_3O_8$), but which form in progressively lower-temperature bodies of **magma** within the earth, and also form **crystals** with different characteristic shapes. Another alkali **feldspar**, sanidine, has the chemical formula $(K,Na)AlSi_3O_8$, and forms in **lava** that has been extruded onto the surface of the earth. The **plagioclase** feldspars all form in molten **rock**, and there is gradation in composition between abite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$). Another common tectosilicate mineral is **quartz** (SiO_2), which forms in many geological environments. Pure quartz is as transparent as **glass**, but varieties include amethyst, which is colored purple by the presence of small amounts of **iron**; rose quartz, which is colored pink by small amounts of titanium, and milky quartz, which appears white due to the presence of small fluid droplets.

TELESCOPE

The telescope is an instrument that collects and analyzes the radiation emitted by distant sources. The most common type is the optical telescope, a collection of lenses and/or mirrors that is used to allow the viewer to see distant objects more clearly by magnifying them or to increase the effective brightness of a faint object. In a broader sense, telescopes can operate at most frequencies of the **electromagnetic spectrum**, from radio waves to gamma rays. The one characteristic all telescopes have in common is the ability to make distant objects appear to be closer (from the Greek *tele* meaning far, and *skopein* meaning to view).

The first optical telescope was probably constructed by the Dutch lens-grinder, **Hans Lippershey**, in 1608. The following year, **Galileo Galilei** built the first astronomical telescope from a tube containing two lenses of different focal lengths aligned on a single axis (the elements of this telescope are still on display in Florence, Italy). With this telescope and several following versions, Galileo made the first telescopic observations of the sky and discovered lunar mountains, four of Jupiter's moons, sunspots, and the starry nature of the Milky Way. Since then, telescopes have increased in size and improved in image quality. Computers are now used to aid in the design of large, complex telescope systems.

The primary function of a telescope is that of light gathering. As will be seen below, resolution limits on telescopes would not call for an aperture much larger than about 30 in (76 cm). However, there are many telescopes around the world with diameters several times this. The reason is that larger telescopes can see further because they can collect more light. For example, the 200 in (508 cm) diameter reflecting telescope at Mt. Palomar, California can gather 25 times more light than the 40 in (102 cm) Yerkes telescope at Williams Bay, Wisconsin, the largest refracting telescope in the world. The more light a telescope can gather, the more distant the objects it can detect, and therefore larger telescopes increase the size of the observable universe.

Unfortunately, scientists are not able to increase the resolution of a telescope simply by increasing the size of the light-gathering aperture to as large a size as needed. Disturbances and nonuniformities in the atmosphere limit the resolution of telescopes to somewhere in the range of 0.5–2 arc seconds, depending on the location of the telescope. Telescope sights on top of mountains are popular because the light reaching the instrument has to travel through less air, and consequently the image has a higher resolution. However, a limit of 0.5 arc seconds corresponds to an aperture of only 12 in (30 cm) for visible light: larger telescopes do not provide increased resolution but only gather more light.

Magnification is not the most important characteristic of telescopes as is commonly thought. The magnifying power of a telescope is dependent on the type and quality of eyepiece being used. The magnification is given simply by the ratio of the focal lengths of the objective and eyepiece. Thus, a 0.8 in (2 cm) focal length eyepiece used in conjunction with a 39 in (100 cm) focal length objective will give a magnification of 50. If the field of view of the eyepiece is 20°, the true field of view will be 0.4°.

Most large telescopes built before the twentieth century were refracting telescopes because techniques were readily available to polish lenses. Not until the latter part of the nineteenth century were techniques developed to coat large mirrors, which allowed the construction of large reflecting telescopes.

Refracting telescopes, i.e. telescopes that use lenses, can suffer from problems of chromatic and other aberrations, which reduce the quality of the image. In order to correct for these, multiple lenses are required, much like the multiple lens systems in a camera lens unit. The advantages of the refracting telescope include having no central "stop" or other diffracting element in the path of light as it enters the telescope, and the alignment and transmission characteristics are stable over long periods of time. However, the refracting telescope can have low overall transmission due to reflection at the surface of all the optical elements, and the largest refractor ever built has a diameter of only 40 in. (102 cm): lenses of a larger diameter will tend to distort under their own weight and give a poor image. Additionally, each lens needs to have both sides polished perfectly and be made from material which is of highly uniform optical quality throughout its entire volume.

All large telescopes, both existing and planned, are of the reflecting variety. Reflecting telescopes have several advantages over refracting designs. First, the reflecting material (usually **aluminum**), deposited on a polished surface, has no chromatic aberration. Second, the whole system can be kept relatively short by folding the light path, as shown in the Newtonian and Cassegrain designs below. Third, the objectives can be made very large since there is only one optical surface to be polished to high tolerance, the optical quality of the mirror substrate is unimportant, and the mirror can be supported from the back to prevent bending. The disadvantages of reflecting systems are: 1) alignment is more critical than in refracting systems, resulting in the use of complex adjustments for aligning the mirrors and the use of **temperature** insensitive mirror substrates, and 2) the secondary or other auxiliary mirrors are mounted on a support structure which occludes part of the primary mirror and causes diffraction.

Catadioptric telescopes use a combination of lenses and mirrors in order to obtain some of the advantages of both. The best-known type of catadioptric is the Schmidt telescope or camera, which is usually used to image a wide field of view for large **area** searches. The lens in this system is very weak and is commonly referred to as a corrector-plate.

The limits to the resolution of a telescope are, as described above, a result of the passage of the light from the distant body through the atmosphere, which is optically nonuniform. Stars appear to twinkle because of constantly fluctuating optical paths through the atmosphere, which results in a variation in both brightness and apparent position. Consequently, much information is lost to astronomers simply because they do not have sufficient resolution from their measurements. There are three ways of overcoming this limitation: setting the telescope out in **space** in order to avoid the atmosphere altogether, compensating for the distortion on a ground-based telescope, and/or stellar interferometry. The first two methods are innovations of the 1990s and are expected to lead to a new era in observational **astronomy**.

The best-known and largest orbiting optical telescope is the **Hubble Space Telescope** (HST), which has an 8 ft (2.4 m) primary mirror and five major instruments for examining various characteristics of distant bodies. After a much-publicized problem with the focusing of the telescope and the installation of a package of corrective optics in 1993, the HST has proved to be the finest of all telescopes ever produced to date. The data collected from HST is of such a high quality that researchers can solve problems that have been in question for years, often with a single photograph. The resolution of the HST is 0.02 arc seconds, a factor of around twenty times better than was previously possible, and also close to the theoretical limit since there is no atmospheric distortion. An example of the significant improvement in imaging that space-based systems have given is the Doradus 30 nebula, which prior to the HST was thought to have consisted of a small number of very bright stars. In a photograph taken by the HST it now appears that the central region has over 3,000 stars.

Another advantage of using a telescope in orbit is that the telescope can detect wavelengths such as the ultraviolet and various portions of the infrared, which are absorbed by the atmosphere and not detectable by ground-based telescopes.

The telescope collects and analyzes the radiation emitted by distant sources. The most common type is the optical telescope, a collection of lenses and/or mirrors that is used to allow the viewer to see distant objects more clearly by magnifying them or to increase the effective brightness of a faint object. ***Photograph by Robert J. Huffman. Field Mark Publications. Reproduced by permission.***

In 1991, the United States government declassified adaptive optics systems (systems that remove atmospheric effects), which had been developed under the Strategic Defense Initiative for ensuring that a laser beam could penetrate the atmosphere without significant distortion.

A laser beam is transmitted from the telescope into a layer of mesospheric sodium at 56–62 mi. (90–100 km) altitude. The laser beam is resonantly backscattered from the volume of excited sodium atoms and acts as a guide-star whose position and shape are well-defined except for the atmospheric distortion. The light from the guide-star is collected by the telescope and a wavefront sensor determines the distortion caused by the atmosphere. This information is then fed back to a deformable mirror, or an array of many small mirrors, which compensates for the distortion. As a result, stars located close to the guide-star come into a focus, which is many times better than can be achieved without compensation. Telescopes have operated at the theoretical resolution limit for infrared wavelengths and have shown an improvement in the visible region of more than 10 times. Atmospheric distortions are constantly changing, so the deformable mirror has to be updated every five milliseconds, which is easily achieved with modern computer technology.

Telescopes collect light largely for two types of analysis: imaging and spectrometry, with the better known being imaging. The goal of imaging is simply to produce an accurate picture of the objects that are being examined. In past years, the only means of recording an image was to take a photograph. For long exposure times, the telescope had to track the sky by rotating at the same speed as Earth, but in the opposite direction. This is still the case today, but the modern telescope no longer uses photographic film but a charged coupled device (**CCD**) array. The CCD is a semiconductor light detector, which is 50 times more sensitive than photographic film and is able to detect single photons. Being fabricated using semiconductor techniques, the CCD can be made very small, and an array typically has a spacing of 15 microns between CCD pixels. A typical array for imaging in telescopes will have a few million pixels. There are many advantages of using the CCD over photographic film or plates, including the lack of a developing stage and that the output from the CCD can be read directly into a computer and the data analyzed and manipulated with relative ease.

The second type of analysis is spectrometry, which means that the researcher wants to know what wavelengths of light are being emitted by a particular object. The reason behind this is that different atoms and molecules emit different wavelengths of light; measuring the spectrum of light emitted by an object can yield information as to its constituents. When performing spectrometry, the output of the telescope is directed to a spectrometer, which is usually an instrument containing a diffraction grating for separating the wavelengths of light. The diffracted light at the output is commonly detected by a CCD array and the data read into a computer.

For almost 40 years, the Hale telescope at Mt. Palomar was the world's largest with a primary mirror diameter of 200 in (5.1 m). During that time, improvements were made primarily in detection techniques, which reached fundamental limits of sensitivity in the late 1980s. In order to observe fainter objects, it became imperative to build larger telescopes, and so a new generation of telescopes is being developed. These telescopes use revolutionary designs in order to increase the collecting area; 2,260 ft^2 (210 m^2) is planned for the European Southern Observatory. This new generation of telescopes will not use the solid, heavy primary mirror of previous designs, whose thickness was between 1/6 and 1/8 of the mirror diameter, but will use a variety of approaches to reduce the mirror weight and improve its thermal and mechanical stability. These new telescopes, combined with quantum-limited detectors, distortion reduction techniques, and coherent array operation, will allow astronomers to see objects more distant than have been observed before.

One of this new generation, the Keck telescope located on Mauna Loa in Hawaii, is currently the largest operating telescope, using a 32 ft (10 m) effective diameter hyperbolic primary mirror constructed from 36 6 ft (1.8 m) hexagonal mirrors. The mirrors are held to relative positions of less than 50 nanometers using active sensors and actuators in order to maintain a clear image at the detector.

Because of its location at over 14,000 ft (4,270 m), the Keck is useful for collecting light over the range of 300–1100 nm. In the late 1990s, this telescope was joined by an identical twin, Keck II, which resulted in an effective mirror diameter of 279 ft (85 m) through the use of interferometry.

Most of the discussion so far has been concerned with optical telescopes operating in the range of 300–1100 nm. However, valuable information is contained in the radiation reaching us at different wavelengths, and telescopes have been built to cover wide ranges of operation, including radio and millimeter waves, infrared, ultraviolet, x rays, and gamma rays.

Infrared telescopes (operating from 1–1000 æm) are particularly useful for examining the emissions from gas **clouds**. Because **water** vapor in the atmosphere can absorb some of this radiation, it is especially important to locate infrared telescopes in high altitudes or in space. In 1983, NASA launched the highly successful Infrared Astronomical **Satellite**, which performed an all-sky survey, revealing a wide variety of sources and opening up new avenues of astrophysical discovery. With the improvement in infrared detection technology in the 1980s, the 1990s will see several new infrared telescopes, including the Infrared Optimized Telescope, a 26.2 ft (8 m) diameter facility, on Mauna Kea, Hawaii.

Several methods are used to reduce the large thermal background which makes viewing infrared difficult, including the use of cooled detectors and dithering the secondary mirror. This latter technique involves pointing the secondary mirror alternatively at the object in question and then at a patch of empty sky. Subtracting the second signal from the first results in the removal of most of the background thermal (infrared) noise received from the sky and the telescope itself, thus allowing the construction of a clear signal.

Radio astronomy was born on the heels of World War II, using the recently developed radio technology to look at radio emissions from the sky. The first radio telescopes were very simple, using an array of wires as the antenna. In the 1950s, the now familiar collecting dish was introduced and has been widely used ever since.

Radio waves are not susceptible to atmospheric disturbances like optical waves are, and so the development of radio telescopes over the past 40 years has seen a continued improvement in both the detection of faint sources as well as in resolution. Despite the fact that radio waves can have wavelengths which are meters long, the resolution achieved has been to the sub-arc second level through the use of many radio telescopes working together in an interferometer array, the largest of which stretches from Hawaii to the United States Virgin Islands (known as the Very Long Baseline Array).

See also Atmospheric composition and structure; SETI; Space and planetary geology

TEMPERATURE AND TEMPERATURE SCALES

Temperature is an indirect measure of the kinetic energy of particles composing matter. The SI unit for temperature is the kelvin (K). There is no degree sign associated with the kelvin.

Kinetic-molecular theory asserts that temperature is a property of matter that results from molecule motion (kinetic energy) and/or atomic vibration. A common misconception is that at absolute zero (0 Kelvin), atomic and molecular motion ceases. In reality, although absolute zero represents the absence of kinetic energy, it represents only the absolute minimal state of molecular or atomic vibration (i.e., electrons still "orbit" the nucleus and nuclear processes including transformations are possible). Temperature is the size-independent quantity that indirectly relates the average kinetic energy of all the particles within a body. Its size-independence stems from the fact that two objects made of the same matter at the same temperature (i.e., objects in thermal equilibrium) will have the same average kinetic energy of constituent particles.

Temperature is commonly measured with a thermometer—a device designed to relate the expansion of liquids (e.g., the rising of mercury in a tube) to changes in temperature. One of the first attempts at articulating a universal temperature scale was made by the Greek scientist and physician Galen (ca. A.D. 170). Galen based his scale on comparative temperatures with an equal mixture of **ice** and **water** assuming the center of a four point scale. By the mid-seventeenth century, Italian scientists and builders fashioned crude alcohol-in-glass thermometers and the English scientist Robert Hooke utilized an alcohol-in-glass thermometer with zero assigned to the **freezing** point of water in meteorological experiments.

During the early eighteenth century, Danish astronomer Ole Roemer advanced a temperature scale based on two points, an assigned temperature of crushed ice and the boiling point of water.

German-born physicist (born in what is now Danzig or Gdansk, Poland) **Daniel Gabriel Fahrenheit** (1686–1736) began creating thermometers containing mercury. Fahrenheit utilized mercury's ability to be easily visualized in **glass** tubing and its ability to remain a liquid over a wide range of normal atmospheric temperatures. Fahrenheit eventually designated the boiling point of water to be 212 degrees. Later he measured the freezing point of water to be 32 degrees, 180 degrees below the boiling point of water. The deviations on the scale were later named after its creator, and the scale is read in degrees Fahrenheit. The Fahrenheit scale still exists today, but is primarily used in the United States for reporting the **weather**. The Celsius and Kelvin temperature scales are more commonly used in scientific investigation.

In 1745, Swedish naturalist **Carl von Linné** (also known as Carl Linnaeus) (1707–1778) devised a *centigrade* (Latin for "one hundred steps") scale to measure temperature. He began his scale with the freezing point of water at zero degrees and set the boiling point of water at 100 degrees. Andrew Celsius used the same number of deviations in his scale, but he instead reversed the order to where the boiling point was zero and the freezing point was 100.

Subsequently, the International Committee of Paris adopted measurements of the freezing point and of the boiling point of water as fundamental markers for temperature scales. The Celsius scale was reversed, and in 1948 was revised to set the triple point of water (that temperature where solid, liquid and gas phases exist in equilibrium) at 0.01°C, and the boiling point of water at 99.975°C. The Celsius scale is used primarily in scientific investigation worldwide and in weather reporting for daily atmospheric temperatures everywhere but the United States.

In order to convert temperature from Celsius to Fahrenheit, the following formula is used:

$°F = 1.8\ (°C) + 32.$

In order to convert temperature from Fahrenheit to Celsius, the following formula is used:

$°C = 5/9\ (°F - 32).$

The necessity for an absolute temperature scale emerged from the advancement of kinetic-molecular theory. The thermodynamic temperature scale—incorporating the concept of absolute zero—evolved and is now accepted as the fundamental measure of temperature. In 1933, the International Committee of Weights and Measures adopted the triple point, or freezing point, of water as 273.16 Kelvin, named after Scottish physicist William Thomson (Lord Kelvin) (1824–1907).

In order to convert temperature to Kelvin from Celsius, the following formula is used:

$K = C + 273.15$

The absolute, or Kelvin, scale is used primarily in conjunction with the Celsius scale because the deviations are equal in magnitude.

In addition to thermometers, other devices can be used measure temperature. Changes in gas volume (e.g., as used in a constant-pressure gas thermometer), electrical resistance to current passage, and thermocouple voltage generation can also be calibrated to changes in temperature.

Another absolute temperature scale (i.e., a scale that incorporates absolute zero) still cited in literature is the Rankine scale. The Rankine is an absolute temperature scale where degree increments are the same magnitude as Fahrenheit degree increments. On the Rankine scale, the freezing point of water at standard temperature and pressure is 491.67°R and the normal boiling point is 671.67°R.

See also Atmospheric chemistry; Atmospheric inversion layers; Atmospheric lapse rate; Atomic theory; Chemistry; Energy transformations; Freezing and melting; Geothermal energy; Geothermal gradient; Quantum theory and mechanics

TERESHKOVA, VALENTINA (1937-)

Russian cosmonaut

Valentina Tereshkova was the first woman in **space**. Tereshkova took off from the Tyuratam Space Station in the *Vostok VI* in 1963 and orbited the Earth for almost three days, showing women had the same resistance to space as men. She then toured the world promoting Soviet science and feminism, and served on the Soviet Women's Committee and the Supreme Soviet Presidium. Valentina Vladimirovna "Valya" Tereshkova was born in the Volga River village of Maslennikovo. Her father, Vladimir Tereshkov, was a tractor driver; a Red Army soldier during World War II, he was killed when Valentina was two. Her mother Elena Fyodorovna Tereshkova, a worker at the Krasny Perekop cotton mill, single-handedly raised Valentina, her brother Vladimir, and her sister Ludmilla in economically trying conditions. Assisting her mother, Valentina was not able to begin school until she was ten.

Tereshkova later moved to her grandmother's home in nearby Yaroslavl, where she worked as an apprentice at the tire factory in 1954. In 1955, she joined her mother and sister as a loom operator at the mill; meanwhile, she graduated by correspondence courses from the Light Industry Technical School. An ardent Communist, she joined the mill's Komsomol

Valentina Tereshkova. *© Hulton-Deutsch Collection/Corbis. Reproduced by permission.*

(Young Communist League), and soon advanced to the Communist Party.

In 1959, Tereshkova joined the Yaroslavl Air Sports Club and became a skilled amateur parachutist. Inspired by the flight of Yuri Gagarin, the first man in space, she volunteered for the Soviet space program. Although she had no experience as a pilot, her 126-jump record gained her a position as a cosmonaut in 1961. Four candidates were chosen for a one-time woman-in-space flight; Tereshkova received an Air Force commission and trained for 18 months before becoming chief pilot of the *Vostok VI*. Admiring fellow cosmonaut Yuri Gagarin was quoted as saying, "It was hard for her to master rocket techniques, study spaceship designs and equipment, but she tackled the job stubbornly and devoted much of her own time to study, poring over books and notes in the evening."

At 12:30 PM on June 16, 1963, Junior Lieutenant Tereshkova became the first woman to be launched into space. Using her radio callsign Chaika (Seagull), she reported, "I see the horizon. A light blue, a beautiful band. This is the Earth. How beautiful it is! All goes well." She was later seen smiling on Soviet and European TV, pencil and logbook floating weightlessly before her face. *Vostok VI* made 48 orbits (1,200,000 miles) in 70 hours, 50 minutes, coming within 3.1 miles of the previously launched *Vostok V*, piloted by cosmonaut Valery Bykovsky. Tereshkova's flight confirmed Soviet test results that women had the same resistance as men to the physical and psychological stresses of space.

Upon her return, she and Bykovsky were hailed in Moscow's Red Square. On June 22, at the Kremlin, she was named a Hero of the Soviet Union and was decorated by Presidium Chairman Leonid Brezhnev with the Order of Lenin and the Gold Star Medal. A symbol of emancipated Soviet feminism, she toured the world as a goodwill ambassador promoting the equality of the sexes in the Soviet Union, receiving a standing ovation at the United Nations. With Gagarin, she traveled to Cuba in October as a guest of the Cuban Women's Federation, and then went to the International Aeronautical Federation Conference in Mexico.

On November 3, 1963, Tereshkova married Soviet cosmonaut Colonel Andrian Nikolayev, who had orbited the earth 64 times in 1962 in the Vostok III. Their daughter Yelena Adrianovna Nikolayeva was born on June 8, 1964, and was carefully studied by doctors fearful of her parents' space exposure, but no ill effects were found. After her flight, Tereshkova continued as an aerospace engineer in the space program; she also worked in Soviet politics, feminism, and culture. She was a Deputy to the Supreme Soviet between 1966 and 1989, and a People's Deputy from 1989 to 1991. Meanwhile, she was a member of the Supreme Soviet Presidium from 1974 to 1989. During the years from 1968 to 1987, she also served on the Soviet Women's Committee, becoming its head in 1977. Tereshkova headed the USSR's International Cultural and Friendship Union from 1987 to 1991, and subsequently chaired the Russian Association of International Cooperation.

Tereshkova summarized her views on women and science in her 1970 "Women in Space" article in the American journal *Impact of Science on Society*: "I believe a woman should always remain a woman and nothing feminine should be alien to her. At the same time I strongly feel that no work done by a woman in the field of science or culture or whatever, however vigorous or demanding, can enter into conflict with her ancient 'wonderful mission'—to love, to be loved—and with her craving for the bliss of motherhood. On the contrary, these two aspects of life can complement each other perfectly.''

See also Spacecraft, manned

TERMINAL MORAINE • *see* MORAINES

TERMINATOR • *see* SOLAR ILLUMINATION: SEASONAL AND DIURNAL PATTERNS

TERRA SATELLITE AND EARTH OBSERVING SYSTEMS (EOS)

To facilitate new research and enhance existing data regarding the interaction of dynamic geophysical systems, NASA is in the process of developing a comprehensive Earth Observing System (EOS). A multi-component program, one of the unifying aims of EOS units is to measure the impact of human activities on Earth's geological and atmospheric processes.

The first component in the EOS array of **remote sensing** instruments is the Terra **satellite**, launched into a near-circular, sun-synchronous Earth orbit in December, 1999.

The development of NASA's EOS (a part of NASA's Earth Sciences Enterprise [ESE]) will result in a group of satellites—each designed for a specific research purpose—that together will feed data to the Earth Observing System Data and Information System (EOSDIS) network that will make the information available to research groups around the world. As of April 2002, three EOS satellites were established in Earth orbit. NASA eventually plans to expand the EOS program to include some 18 satellites.

Terra's instrumentation includes an Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), a Multi-angle Imaging Spectro-Radiometer (MISR), a **Clouds** and the Earth's Radiant Energy System (CERES) monitor, a Moderate-resolution Imaging Spectroradiometer (MODIS), and a Measurements of Pollution in the **Troposphere** (MOPIT) sensor.

ASTER is able to gather high-resolution Earth images ranging across the **electromagnetic spectrum** from visible to thermal infrared light. ASTER data will facilitate the development of maps based upon surface temperatures. MISR measures sunlight scattering from nine different angles. CERES, a two-component package, each of which scans radiation flux in different modes. MODIS provides wide-angle measurements in 36 spectral bands than will provide accurate estimates of phenomena such as cirrus cloud cover. At present, the extent of cirrus cloud cover is an important part of research efforts to determine whether they have a net cooling or warming effect on Earth's atmosphere. MODIS is capable of providing data enabling estimation of photosynthetic activity that in turn allows estimates of atmospheric **carbon dioxide** levels. MODIS is also capable of accurately measuring the extent of snow cover, or in the detection of heat from **volcanic eruptions** and fires. MOPITT utilizes gas **correlation spectroscopy** data in measuring radiation from Earth in three specific spectral bands. MOPITT data allows estimations of **carbon** monoxide and other gas (e.g., methane) levels in the troposphere.

In March 2002, the Terra satellite's Multi-angle Imaging Spectro Radiometer (MISR) instrument recorded data confirming the calving (breakaway) of a major iceberg measuring almost 200 mi^2 (5200 km^2) off the Antarctic **ice** shelf. The iceberg, designated B-22, broke away from the West Antarctic mainland into the Amundsen Sea. In an effort to estimate and evaluate the effects of **climate** warming, researchers are attempting to correlate—and/or determine the cause of—a recent reported increase in iceberg calvings during the last decade of the twentieth century. As of May 2002, data was insufficient to positively determine a causal relationship to potential human-induced **global warming**. In fact, part of the EOS mission is to develop a database that will enable researchers to determine whether such dramatic events as the breakaway of B-22 was a result of global warming or an expected occurrence that is a normal part of cyclic regional climatic variation.

See also Atmospheric composition and structure; Atmospheric pollution; Insolation and total solar irradiation; Scientific data management in Earth Sciences; Spectroscopy; Weather balloon; Weather satellite

TERTIARY PERIOD

In **geologic time**, the Tertiary Period (also sometimes referred to in terms of a Paleogene Period and a Neogene Period), represents the first geologic period in the **Cenozoic Era**. The Tertiary Period spans the time between roughly 65 million years ago (mya) and 2.6 mya. When referred to in terms of a Paleogene Period and a Neogene Period, the Paleogene Period extends from approximately 65 mya to 23 mya, and the Neogene Period from 23 mya to 2.6 mya.

The Tertiary Period contains five geologic epochs. The earliest epoch, the **Paleocene Epoch**, ranges from approximately 65 mya to 55 mya. The Paleocene Epoch is further subdivided into (from earliest to most recent) Danian and Thanetian stages. The second epoch, the **Eocene Epoch** ranges from approximately 55 mya to 34 mya. The Eocene Epoch is further subdivided into (from earliest to most recent) Ypresian, Lutetian, Bartonian, and Priabonian stages. The third epoch of the Tertiary Period, the **Oligocene Epoch** ranges from approximately 34 mya to 23 mya. The Oligocene Epoch is further subdivided into (from earliest to most recent) Rupelian and Chattian stages. Following the Oligocene Epoch, the **Miocene Epoch** ranges from approximately 23 mya to 5 mya. The Miocene Epoch is further subdivided into (from earliest to most recent) Aquitanian, Burdigalian, Langhian, Serravallian, Tortonian, and Messinian stages. The last epoch of the Tertiary Period is the **Pliocene Epoch**. The Pliocene Epoch is further subdivided into Zanclian and Placenzian stages.

The onset of the Tertiary Period is marked by the K-T boundary or K-T event—a large mass extinction. Most scientists argue that the K-T extinction resulted from—or was initiated by—a large asteroid impact in the oceanic basin near what is now the Yucatan Peninsula of Mexico. The remains of the **impact crater**, termed the Chicxulub crater, measures more than 105 mi (170 km) in diameter. The impact caused widespread firestorms, earthquakes, and tidal waves. Post-impact damage to Earth's ecosystem occurred as dust, soot, and debris from the collision occluded the atmosphere to sunlight. The global darkening was sufficient to inhibit photosynthesis. Widespread elimination of plant species caused repercussions throughout the food chain as starvation resulted in extinction of the largest life forms with the greatest metabolic energy needs (e.g., the dinosaurs).

At end of the prior **Cretaceous Period** and during the first half of the Tertiary Period (i.e. the Paleogene Period), Earth suffered a series of intense and large impacts. Large impact craters (greater than 25 mi or 40 km in diameter) include the Kara and Popigal craters in Russia, the Chesapeake crater in Maryland, and the Montagnais crater in Nova Scotia.

The last major impact crater with a diameter over 31 mi (50 km) struck Earth near what is now Kara-Kul, Tajikistan at end of the Tertiary Period and the start of the **Quaternary Period**.

The extinction of the dinosaurs and many other large species allowed the rise of mammals as the dominant land species during the Tertiary Period.

At the beginning of the Tertiary Period, North America and **Europe** were separated by a widening ocean basin spreading along a prominent mid-oceanic ridge. **North America** and **South America** were separated by a confluence of the future Pacific Ocean and Atlantic Ocean, and extensive flooding submerged much of what are now the eastern and middle portions of the United States. By the start of the Tertiary Period, **water** separated South America from **Africa**, and the Australian and Antarctic continents were clearly articulated. The Antarctic continent had begun a southward migration toward the south polar region. At the outset of the Tertiary Period, the Indian subcontinent remained far south of the Euro-Asiatic continent.

By the middle of the Tertiary Period (approximately 30 mya), the modern continental arrangement was easily recognizable. Although still separated by water, the Central American land bridge between North and South America began to reemerge. **Antarctica** assumed a polar position and extensive **ice** accumulation began on the continent. The Indian plate drove rapidly northward of the equator to close with the Asiatic plate. Although still separated by a shallow strait of water, the impending collision of the plates that would eventually form the Himalayan mountain chain had begun. The gap between North America and Europe continued to widen at a site of **sea-floor spreading** along a prominent mid-Atlantic ridge. By the middle of the Tertiary Period, the mid-Atlantic ridge was apparent in a large suture-like extension into the rapidly widening South Atlantic Ocean that separates South America from Africa.

By the end of the Tertiary Period, approximately 2.6 mya, Earth's continents assumed their modern configuration. The Pacific Ocean separated **Asia** and **Australia** from North America and South America, just as the Atlantic Ocean separated North and South America from Europe (Eurasian plate) and Africa. The Indian Ocean washed between Africa, India, Asia, and Australia. The Indian plate driving against and under the Eurasian plate uplifted both, causing rapid mountain building. As a result of the ongoing collision, ancient oceanic **crust** bearing marine **fossils** was uplifted into the Himalayan chain.

Climatic cooling increased at the end of the Tertiary Period, and modern **glaciation** patterns became well-established.

See also Archean; Cambrian Period; Dating methods; Devonian Period; Evolution, evidence of; Evolutionary mechanisms; Fossils and fossilization; Historical geology; Holocene Epoch; Jurassic Period; Mesozoic Era; Mississippian Period; Ordovician Period; Paleozoic Era; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Precambrian; Proterozoic Era; Silurian Period; Supercontinents; Triassic Period

THERMOSPHERE

Based on the vertical **temperature** profile in the atmosphere, the thermosphere is the highest layer, located above the **mesosphere**. While in the **troposphere** and the mesosphere, the temperature decreases with altitude. In the **stratosphere** and thermosphere the temperature increases with height (called temperature inversion). It is separated from the mesosphere by the mesopause, in which the temperature does not change much vertically. Above the thermosphere, the upper limit of the atmosphere, the exosphere can be found blending into **space**. The upper part of the mesosphere and a big part of the thermosphere overlap with the **ionosphere**, which is a region defined on the basis of electric properties. The thermosphere and the exosphere together form the upper atmosphere.

Among the four atmospheric temperature-defined layers, the thermosphere is located highest above Earth's surface, beginning at about 57 mi (90 km) above Earth, and reaching into about 300 mi (500 km) height. The name of this layer, thermosphere, originates from the Greek *thermo*, meaning heat, because in this layer the temperature increases with altitude reaching temperatures higher than 1830°F (1000°C). In the thermosphere, **oxygen** molecules absorb the energy from the Sun's rays, which results in the warming of the air. Because there are relatively few molecules and atoms in the thermosphere, even absorbing small amounts of **solar energy** can significantly increase the air temperature, making the thermosphere the hottest layer in the atmosphere. Above 124 mi (200 km), the temperature becomes independent of altitude.

Because the thermosphere and exosphere belong to the upper atmosphere, the density of the air in addition to the **atmospheric pressure** is greatly reduced when compared to the atmosphere at Earth's surface. At these high altitudes, the atmospheric gases tend to sort into layers according to their molecular mass, and chemical reactions happen much faster here than near the surface of the earth.

See also Atmospheric composition and structure

THOMSON, LORD KELVIN, WILLIAM
(1824-1907)
Scottish physicist

William Thomson, known to history as Lord Kelvin, was granted the first scientific peerage by Queen Victoria in 1892 for his unique consulting work that made possible the installation of the transatlantic cable linking the telegraph systems of America and England. The peerage was created especially for him, taking the name from the Kelvin River near Glasgow, Scotland. Thus, when Thomson's proposal for an absolute scale measuring heat was widely accepted, it was given the name Kelvin.

Thomson was a child prodigy who grew up in the environment of academia and became a professor at a young age. Thomson was enthusiastic and dramatic in his teaching style. Known as an expert on the dynamics of heat, he was also noted for having a wide range of interests in the sciences, particularly **electricity and magnetism**. As a science and technology authority, Thomson was willing to take on the unpopular side of a controversy. This characteristic almost ruined his career when he attempted to establish the age of Earth, accepting the least popular premise concerning the origins of the planet. However, his gamble in supporting James Prescott Joule rewarded Thomson with a lifelong friendship and a proficient research collaboration.

Thomson was born in Belfast, Northern Ireland, in 1807. While he was still young, the family moved to Glasgow where his father received a position as a mathematics professor. His mother died when he was six years old, and young William became accustomed to attending his father's lectures. After attending his father's classes for many years, Thomson surprised many by actively participating. By age ten, he was ready for college. He was able to keep up with his much older classmates and he even surpassed them by writing his first scholarly treatise at the age of fourteen. Many were impressed with this work and a respected professor, representing Thomson, presented it in lecture to the Royal Society of Edinburgh. Thomson and his professors decided he should not present the paper himself because his young age would have undermined the respect his paper deserved.

After enrolling in Peterhouse College at age seventeen, Thomson achieved honors in a difficult mathematics program by age 21. Although his father had hoped that William would follow him into mathematics, Thomson was strongly interested in natural philosophy (as science was called in his time). He was very much interested in Fourier and other newly emerging theories of heat, having already achieved valuable experience at Regnault's Laboratory in Paris. Thus, when offered a position as professor of natural philosophy at the University of Glasgow in 1846, Thomson accepted. He remained a professor at Glasgow for the next fifty-eight years.

Thomson's first achievement as a professor was an attempt to establish the age of Earth based on mathematical models representing the difference in **temperature** between Earth and the **Sun**. This research was almost a fiasco, upsetting well-respected geologists of the day. Although Thompson's basic geological premise was faulty, his proficient models and accurate calculations were impressive. More importantly, the principles of thermodynamics he employed were well thought out. Fortunately, because many paid attention to the strengths of his study, Thomson advanced his expertise on the properties and dynamics of heat.

At Glasgow, Thomson's students were fascinated with his youthfulness and his energetic lecturing style. He built his own laboratory for his students by converting an old wine cellar belonging to a more established member of the faculty.

In 1847, at a conference of the British association, Thomson listened as Joule presented findings on the effects of heat on gases. Joule's presentation was not convincing to most of the assembled scientists and he would have been ignored if Thomson had not come to his defense. Thomson not only supported Joule in this conference, but also agreed to collaborate with him on new research. From this work came the Joule-Thomson effect of heat conservation, presented in a paper in 1851. This concept—that gas allowed to expand in a vacuum will reduce its heat—became the foundation of an early refrigeration industry.

While studying the effects of heat on gases, Thomson recognized that the linear relationship between the heat and mass in gases was awkwardly graphed using the traditional Celsius Scale. In 1848, he proposed an absolute scale using the same range as the Celsius scale but with zero set at the point where there is virtually no movement among the molecules (–273.18°C). This can be considered the point of absolutely no heat. In 1851, Thomson further elaborated how this new scale would illustrate the principles of thermodynamics more clearly in experiments. Scientists in other fields also recognized how the absolute (later called Kelvin) scale could be very useful.

Thomson admitted that he learned much from Joule. However, for many years he tried to resolve the theoretical differences between the dynamic theories of heat that Joule was relying on and the principles he found to be true in the theories of Sadi Carnot. In his dissertation of 1851, he thoroughly presented the strengths of Carnot's theories reconciled to the dynamic theory. From this paper, the second law of thermodynamics was established. This law stated that heat transferred from hotter matter to colder matter has to release mechanical work. Furthermore, heat taken from colder matter to hotter matter requires the input of mechanical work. However, the second law of thermodynamics was not fully credited to Thomson because it was contemporaneously developed (separate from Thomson's work) by other researchers.

Thomson also excelled in other areas of science. His improvements in the conductivity of cable and in galvanometers were patented inventions without which the practicality of the transatlantic cable would not have been possible. Among Thomson's many honors, he was elected president of the Royal Society and held the post from 1890 to 1894. He continued to invent and study in his later life. After a short period of retirement from the university, he returned as a graduate student. Although Thomson maintained a sharp mind until his death, he was adamant against the changes in old paradigms that new discoveries brought at the end of the nineteenth century. For example, Thomson once remarked that air travel other than ballooning would be a scientific impossibility. Thomson died in 1907 and was buried in Westminster Abbey, leaving no children to inherit his title.

See also Physics; Temperature and temperature scales

THUNDER

Thunder is the noise caused by **lightning** in a thunderstorm, when the release of heat energy results in audible shock waves in the air.

A thunderstorm is a storm that produces lightning and thunder, and occurs in cumulonimbus **clouds**. Cumulonimbus clouds are large, tall clouds with very strong updrafts that transport **water** high into the atmosphere. Thunderstorms can also produce flash **floods**, hail, strong winds, and even tornadoes. At any time on Earth, about 2,000 thunderstorms are taking place, from mild rainstorms to very damaging hailstorms with high winds. In general, the higher the storm clouds, the more violent the resulting storm will follow. Under certain conditions, isolated thunderstorms can even merge to form large convective complexes with increasing power and damage capabilities. Thunderstorms and lightning can cause not only billions of dollars of damage every year, but also result in loss of human and animal life, since about 100 people die per year in the United States from causes associated with lightning.

Lightning is a large electrical discharge produced by thunderstorms as a huge spark, which can heat the air as much as several times hotter than the **temperature** of the surface of the **Sun** (about 54,000°F or 30,000°C). This heated air causes expansion in the air when the electrical charge of lightning passes through it, and forces the air molecules to expand. As they expand, the air molecules require more space and they bump into cooler air, creating an airwave, the sound of thunder. It travels in all directions from the lightening at the speed of the sound (330 m/s); therefore, it takes the thunder about five seconds to travel each mile, or about three seconds to travel one kilometer. Because light travels faster than sound, the lightning is always seen first, before the thunder is heard. Measuring the time between the lightning and the thunder can give an approximate estimate of how far the observer is from the thunderstorm.

Depending on the location of the observer or the type of lightning, thunder can produce many different sounds. When lightning strikes nearby, the resulting thunder is usually interpreted as a short and loud bang, whereas thunder is interpreted as a long, low rumble when it is heard from far away. Thunder can also sound like a large crack, or a clap of thunder followed by rumbling, or a thunder roll. Lightning always produces thunder, and without lightning, there is no thunder in a thunderstorm. Sometimes, when the lightning is too far away for the sound waves to reach the observer, lightning can be seen but no thunder can be heard. This is known commonly as heat lightning, and it happens because the dissipating sound of thunder rarely travels farther than ten miles, especially in lowlands or at sea.

See also Clouds and cloud types; Weather forecasting

TIDES

Tides are deformations in the shape of a body caused by the gravitational force of one or more other bodies. At least in theory, any two bodies in the Universe exert such a force on each other, although obvious tidal effects are generally too small to observe. By far the most important examples of tidal forces as far as humans are concerned are ocean tides that occur on Earth as a result of the **Moon** and Sun's gravitational attraction.

The side of Earth facing the Moon, due to the Moon's proximity, experiences a larger gravitational pull, or force, than other areas. This force causes ocean **water**, since it is able to flow, to form a slight bulge, making the water in that **area** slightly deeper. At the same time, another bulge forms on the opposing side of the Earth. This second bulge, which is perhaps a bit harder to understand, forms due to centrifugal force. Contrary to popular belief, the Moon does not revolve around the Earth, but rather the Earth and Moon revolve about a common point that is within the Earth, but nowhere near its center (2880 miles or 4640 km away). When you twirl a ball above your head at the end of a piece of string, the ball pulls against the string. This pull is known as centrifugal force.

When the Earth-Moon system revolves around its common axis, the side of Earth that is farthest from the Moon experiences a centrifugal force, like a ball spinning at the end of a string. This force causes a second tidal bulge to form, which is the same size as the first. The result is that two lunar tidal bulges exist on Earth at all times—one on the side of the Earth facing the Moon and another directly opposite to it. These bulges account for the phenomenon known as high tide.

The formation of these two high tide bulges causes a belt of low water to form at 90° to the high tide bulges. This belt, which completely encircles the Earth, produces the phenomenon known as low tide.

As Earth rotates on its axis, land areas slide underneath the bulges, forcing the **oceans** up over some coastlines and beneath the low tide belt, forcing water out away from other coastlines. In a sense, as Earth rotates on its axis, the high tide bulges and the low tide belt remains stationary and the continents and ocean basins move beneath them. As a result, most coastal areas experience two high tides and two low tides each day.

In addition to the lunar bulges, the **Sun** forms its own tidal bulges, one due to gravitational force and the other due to centrifugal force. However, due to the Sun's much greater distance from the Earth, its tidal effect is approximately one half that of the Moon.

When the Moon and Sun are in line with each other (new Moon and full Moon), their gravitational, or tidal forces, combine to produce a maximum pull. The tides produced in such cases are known as spring tides. The spring high tide produces the highest high tide and the spring low tide produces the lowest low tide of the fortnight. This is the same as saying the spring tides have the greatest tidal range, which is the vertical difference between high tide and low tide.

When the Moon and Sun are at right angles to each other (first and third quarter Moon), the two forces act in opposition to each other to produce a minimum pull on the oceans. The tides in this case are known as neap tides. The neap high tide produces the lowest high tide and the neap low tide produces the highest low tide, or the smallest tidal range, of the fortnight.

It is now possible to write very precise mathematical equations that describe the gravitational effects of the Moon and the Sun. In theory, it should be possible to make very precise predictions of the time, size, and occurrence of tides. In fact, however, such predictions are not possible because a large number of factors contribute to the height of the oceans at high and low tide at a particular location. Primary among these is that the shape of ocean basins is so irregular that water does not behave in the "ideal" way that mathematical equations would predict. However, a number of other variables also com-

Boats beached at Low Tide, La Flotte, lle de Re, France. ***Photograph by Nik Wheeler. Corbis Corporation (Bellevue). Reproduced by permission.***

plicate the situation. These include variations in the Earth's axial **rotation**, and variations in Earth-Moon-Sun positioning, including variations in orbital distance and inclination.

Scientists continue to improve their predictions of tidal variations using mathematical models based on the equilibrium theory of tides. However, for the present, estimates of tidal behavior are still based on previous tidal observations, continuous monitoring of coastal water levels, and astronomical tables. This more practical approach is referred to as the dynamical theory of tides, which is based on observation rather than mathematical equations.

The accumulated information about tidal patterns in various parts of the world is used to produce tide tables. Tide tables are constructed by looking back over past records to find out for any given location the times at which tides have occurred for many years in the past and the height to which those tides have reached at maximum and minimum levels. These past records are then used to predict the most likely times and heights to be expected for tides at various times in the future for the same locations. Because of differences in ocean bottoms, coastline, and other factors, unique tide tables must be constructed for each specific coastline every place in the world. They can then be used by fishermen, those on ocean liners, and others who need to know about tidal actions.

In most places, tides are semidiurnal, that is, there are two tidal cycles (high and low tides) each day. In other words, during a typical day, the tides reach their highest point along the shore and their lowest point twice each day. The high water level reached during one of the high tide stages is usually greater than the other high point, and the low water level reached during one of the low tide stages is usually less than the other low tide point. This consistent difference is called the diurnal inequality of the tides.

In a few locations, tides occur only once a day, with a single high tide stage and a single low tide stage. These are known as diurnal tides. In both diurnal and semidiurnal settings, when the tide is rising, it is called the flood tide. When the tide is falling, it is the ebb tide. The point when the water reaches its highest point at high tide, or its lowest point at low tide, is called the slack tide, since the water level is static, neither rising nor falling, at least for a short time.

As the Moon revolves around the Earth, the Earth also rotates on its axis. Consequently, the Earth must rotate on its axis for 24 hours, 50 minutes, known as a lunar day, to return to the same position relative to the Moon above. The additional 50 minutes allows Earth to “catch up” to the Moon, so to speak. In other words, if the Moon was directly overhead at Boston, Massachusetts, at noon yesterday, it will again be above Boston at 12:50 PM today. As a result, on a coast with diurnal tides, each day the high tide (or low tide) will occur 50 minutes later than the day before. Whereas, on a semidiurnal coast, each high tide (or low tide) will occur 12 hours, 25 minutes later than the previous high one.

The movement of ocean water as a result of tidal action is known as a tidal current. In open water, tidal currents are relatively weak and tend to change direction slowly and regularly throughout the day. They form, therefore, a kind of rotary current that sweeps around the ocean like the minute hand on a clock. Closer to land, however, tidal currents tend to change direction rather quickly, flowing toward land during high tide and away from land during low tide. In many cases, this onshore and offshore tidal current flows up the mouth of a river or some other narrow opening. The tidal current may then attain velocities as great as 9 mi (15 km) an hour with crests as high as 10 ft (3 m) or more.

Most tides attain less than 10 ft in size; 3–10 ft (1–3 m) is common. In some locations, however, the tides may be much greater. These locations are characterized by ocean bottoms that act as funnels through which ocean waters rush upward towards or downward away from the shore at very rapid speeds. In the Bay of Fundy, between Nova Scotia and New Brunswick, for example, the difference between high and low tides, the tidal range, may be as great as 46 ft (14 m). In comparison, some large bodies of water, such as the Mediterranean, Baltic, and Caribbean **Seas**, have areas with tides of less than 1 ft (0.3 m). All coastal locations (as well as very large **lakes**) experience some variation in tidal range during a fortnight due to the affects of neap versus spring tides.

See also Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Gravity and the gravitational field; Marine transgression and marine regression

TILL

Till is the general term for any sediments that were deposited solely by glacial **ice**. Till is distinguished from other glacial deposits formed by forces other than ice, such as glaciofluvial (or glacial melt **water**) deposits. A similar term is moraine, but it connotes more specific depositional mechanisms and spatial relationships to the glacier than does till.

Tills are produced by virtue of the formation, advance, and retreat of **glaciers**. The immense weight of an advancing glacier causes it to rip up **rock** and **soil** and incorporate them into the ice. These sediments then migrate forward as the glacier creeps downhill. When sediments reach the leading edge of the glacier where it is constantly **melting**, they are turned out as till.

This depositional mechanism results in tills being characterized by a physical heterogeneity; the sediments are unsorted, random in size, and may consist of a large range in particle size—from tiny clays to huge boulders. Tills are also generally unstratified, showing no sedimentary layering. The sediments in till exhibit a variable degree of rounding to the sediments, although some rounding is almost always observed. Despite their random origin, tills sometimes exhibit some degree of consistency in composition, allowing them to be described by the dominant size sediment they contain, such as gravelly or sandy tills.

Although tills may contain rocks from anywhere the glacier came in contact with, and sometimes do show evidence of sources hundreds of miles away, most tills are locally derived. They usually consist of rocks and soils picked up by the glacier within a few miles of where they were deposited. As a result, tills often provide evidence of the local **bedrock** and aid in determining the **geology** of areas that are now covered with glacial deposits.

See also Glacial landforms; Glaciation

TIME ZONES

Earth rotates on its **polar axis** once every 23.9345 hrs. As an oblate sphere measuring a circumferential 360°, Earth rotates through almost 15 angular degrees per hour.

Local noon occurs when, on the hypothetical celestial sphere, the **Sun** is at the highest point during its daily skyward arch from east to west. When the Sun is at its zenith on the celestial meridian, this is termed local noon. In the extreme, every line of longitude, or fraction thereof, has a different local noon. In practice, however, because of Earth’s angular **rotation** rate, it is more convenient to create a system of 24 time zones—each spanning 15 angular degrees. The central line of longitude in these zones establishes the local noon for individual time zones.

Earth’s lines of longitude (meridians) are great circles that meet at the north and south polar axis. They are referenced by an east or west displacement from the prime meridian. Accordingly, lines of longitude range from 0° E to 180° E and 0° W to 180° W. Degrees are further divided into arcminutes and arcseconds.

The prime meridian runs through Greenwich, England and the line of longitude displaced 180° E and 180° W from the prime meridian is termed the international dateline. The international dateline generally runs through sparsely islanded areas of the Pacific Ocean.

With regard to the solar meridian, the Sun’s location (and reference to local noon) is described in terms of being ante meridian (A.M.) or post meridian (P.M.).

Standard meridians occur every 15° of longitudinal displacement from the prime meridian (e.g., 15° W, 30° W, 45° W, etc.) The standard meridians also establish the local noon for the time zone and, therefore, each time zone is defined as being 7.5° longitudinal displacement both west and east of the standard meridian. Accordingly, dividing the standard meridian by 15 yields the time correction for that time zone. For example, the standard meridian of 90° W runs near both Chicago and New Orleans. These sites are in the Central Time

Zone of the United States (CST; Central Standard Time). To obtain the proper correction from Greenwich Mean Time (GMT)—also termed Universal Time (UT or UTC)—a division of 90° by 15° means that CST is six hours behind GMT. Accordingly, when it is noon 12:00 HRS GMT in London, it is 0600 HRS (6 A.M.) CST in Chicago or New Orleans. Because of Earth's rotation, displacements west are further designated with a negative sign. Accordingly, CST = GMT – 6 hrs.

Additional North American meridians and time zones include standard meridian 60° W for Atlantic Standard Time (e.g., as for Puerto Rico); standard meridian 75° W for Eastern Standard Time (EST); standard meridian 105° W for Mountain Standard Time (MST); standard meridian 120° W for Pacific Standard Time (PST); standard meridian 135° W for Yukon Standard Time (YST); standard meridian 150° W for Hawaii-Alaska Standard Time (HAST) and standard meridian 165° W for Bering Standard time.

Movement east of the prime meridian results adding time to GMT. For example, Rome, Italy, at a **latitude and longitude** of 42° N, 12° E, is 3° W of the 15° E standard meridian. Because a time zone ranges 7.5° east and west of a standard meridian, the applicable standard meridian for Rome is the 15° E standard meridian. Accordingly, the time differential between Rome and London (GMT) is 15°/15° = 1–interpreted as +1 hour time difference. Therefore, when it is noon in London, it is 1300 HRS, or 1 P.M., in Rome.

In reality, there are many local deviations of the time zone boundaries based upon geopolitical considerations (e.g., state and national boundaries). Actual time corrections are also influenced by whether or not a particular locality adopts daylight saving time shifts (usually one hour) to save energy by shifting daylight hours to clock hours more conductive to typical human work patterns. The United States shifts to Daylight Saving Time between April and October each year. Accordingly, time zone designations are changed from, for example, CST to CDST (Central Daylight Saving Time).

See also Cartography; Celestial sphere: The apparent movements of the Sun, Moon, planets, and stars; Solar illumination: Seasonal and diurnal patterns

TOMBAUGH, CLYDE W. (1906-1997)

American astronomer

Clyde W. Tombaugh, an astronomer and master **telescope** maker, spent much of his career performing a painstaking photographic survey of the heavens from Lowell Observatory in Flagstaff, Arizona. This led to the discovery of Pluto (1930), the ninth planet in the **solar system**. Although Tombaugh is best known for this early triumph, he went on to make other contributions, including his work on the geography of Mars and studies of the distribution of galaxies. Tombaugh also made valuable refinements to missile-tracking technology during a nine-year stint at the U.S. Army's White Sands Proving Grounds in New Mexico.

Clyde William Tombaugh, the eldest of six children, was born to Muron Tombaugh, a farmer, and Adella Chritton Tombaugh. He spent most of his childhood on a farm near Streator, Illinois. In 1922, the family relocated to a farm in western Kansas. Tombaugh glimpsed his first telescopic view of the heavens through his uncle Leon's 3-in (7.6-cm) refractor, a kind of telescope that uses a lens to gather faint light from stars and planets. In 1925, inspired by an article in *Popular Astronomy*, Tombaugh bought materials to grind an 8-in (20.3-cm) light-collecting mirror for a reflecting telescope. He ground that first mirror by hand, using a fence post on the farm as a grinding stand.

The finished instrument, a 7-ft (2.1-m) rectangular wooden box, was equipped with wooden setting circles for aligning it to objects of interest in the sky. Tombaugh had not ground the mirror very accurately, and thus the telescope was unsuitable for the planetary observing he had in mind. However, it launched a lifetime of building, improving, and maintaining telescopes, tasks at which Tombaugh excelled. Tombaugh biographer and amateur astronomer David H. Levy estimated that Tombaugh ground some 36 telescope mirrors and lenses in his career. He continued to use a few of his early telescopes for decades after he first constructed them (for example, his 9-in [23-cm] reflector, whose mechanical mounting included parts from a 1910 Buick).

Tombaugh's 9-in reflector, which he completed in 1928, led to a career as a professional observer as well as to sharper views of the planets and stars. After a 1928 hailstorm wiped out the Tombaughs' wheat crop and foiled Clyde's plans for college, the young observer turned his new telescope to Jupiter and Mars. Subsequently, he sent his best drawings of these planets to Lowell Observatory, which had been founded in the late nineteenth century by famed Mars watcher Percival Lowell.

Hoping only for constructive criticism of his drawings, Tombaugh instead received a job offer from the astronomers at Lowell. He accepted, and in January 1929 began his work on the search for the predicted ninth planet beyond the orbit of Neptune. Working full time as a professional observer (although lacking any formal education in **astronomy**), Tombaugh used Lowell's 13-in (33-cm) telescope to systematically photograph the sky. He then used a special instrument, called a blink comparator, to examine the plates for telltale signs of moving bodies beyond the orbit of Earth. A blink comparator, or blink microscope, rapidly alternates—up to 10 times per second—two photographic images, taken at different times, of the same field or **area** of the sky. Seen through a magnifying lens, moving bodies will appear to jump back and forth or "blink" as the images are switched.

Using his knowledge of orbital mechanics and his sharp observer's eye, Tombaugh was able to discern **asteroids** and **comets** from possible planets; a third "check" plate was then taken to confirm or rule out the existence of these suspected planets. On February 18, 1930, after 10 months of concentrated, painstaking work, Tombaugh zeroed in on Pluto, fulfilling a search begun by Percival Lowell in 1905. The discovery of Pluto secured the 24-year-old Tombaugh's reputation and his place in the history of astronomy, and he remained with the survey until 1943.

After his discovery, Tombaugh took some time off to obtain his formal education in astronomy. He left for the University of Kansas in the fall of 1932, returning to Lowell each summer to resume his observing duties. At college, he met Patricia Irene Edson, a philosophy major. They married in 1934, and subsequently had two children. Tombaugh paused only once more for formal education in science, taking his master's degree in 1939 at the University of Kansas. For his thesis work, he restored the university's 27-in (68.6-cm) reflecting telescope to full operational status and studied its observing capabilities.

In 1943, Tombaugh taught **physics** at Arizona State Teachers College in Flagstaff; that same year, the U.S. Navy asked him to teach navigation, also at Arizona State. In what little spare time remained, Tombaugh struggled to continue the planet survey. The following year, he taught astronomy and the history of astronomy at the University of California in Los Angeles. Tombaugh's stint on the planet survey ceased abruptly in 1946. Citing financial constraints, observatory director Vesto M. Slipher asked Tombaugh to seek other employment.

Tombaugh's contribution to the "planetary patrol" at Lowell proved enormous. From 1929 to 1945, he cataloged many thousands of celestial objects, including 29,548 galaxies, 3,969 asteroids (775 of them previously unreported), two previously undiscovered comets, one nova, and, of course, the planet Pluto. However, as Tombaugh pointed out to biographer David Levy, tiny Pluto cast a long and sometimes burdensome shadow over the rest of his career, obscuring subsequent astronomical work. For instance, in 1937, Tombaugh discovered a dense cluster of 1,800 galaxies, which he called the "Great Perseus-Andromeda Stratum of Extra-Galactic Nebula." This suggested to Tombaugh that the distribution of galaxies in the universe may not be as random and irregular as some astronomers believed at the time.

Tombaugh was also an accomplished observer of Mars. He predicted in 1950 that the red planet, being so close to the asteroid belt, would have impact craters like those on the **moon**. These craters are not easily visible from Earth because Mars always shows its face to astronomers fully or nearly fully lighted, masking the craters' fine lines. Images of the Martian surface captured in the 1960s by the *Mariner IV* **space probe** confirmed Tombaugh's prediction.

In 1946, Tombaugh began a relatively brief career as a civilian employee of the U.S. Army, working as an optical physicist and astronomer at White Sands Proving Grounds near Las Cruces, New Mexico, where the army was developing launching facilities for captured German V-2 missiles. Tombaugh witnessed 50 launchings of the 46-ft (14-m) rockets and documented their performance in flight using a variety of tracking telescopes. Armed with his observing skills and intimate knowledge of telescope optics, Tombaugh greatly increased the quality of missile tracking at White Sands, host to a number of important postwar missile-development programs.

Tombaugh resumed serious planetary observing in 1955, when he accepted a teaching and research position at New Mexico State University in Las Cruces. There, he taught astronomy, led planetary observation programs, and participated in the care and construction of new telescopes. From 1953 to 1958, Tombaugh directed a major search for small, as-yet-undetected objects near the Earth—either asteroids or tiny natural satellites—that might pose a threat to future spacecraft. He and colleagues developed sensitive telescopic tracking equipment and used it to scan the skies from a high-altitude site in Quito, Ecuador. The survey turned up no evidence of hazardous objects near Earth, and Tombaugh issued a closing report on the program the year after the Soviet Union launched *Sputnik* (1957), the first artificial **satellite**.

Upon his retirement in 1973, Tombaugh maintained his links to New Mexico State University, often attending lunches and colloquia in the astronomy department that he helped to found. He also remained active in the local astronomical society and continued to observe with his homemade telescopes. Indeed, asked by the Smithsonian Institution in Washington, D.C., to relinquish his 9-in reflector to its historical collections, Tombaugh refused, explaining to *Smithsonian* magazine, "I'm not through using it yet!" He died in 1997 at his home in Las Cruces, New Mexico.

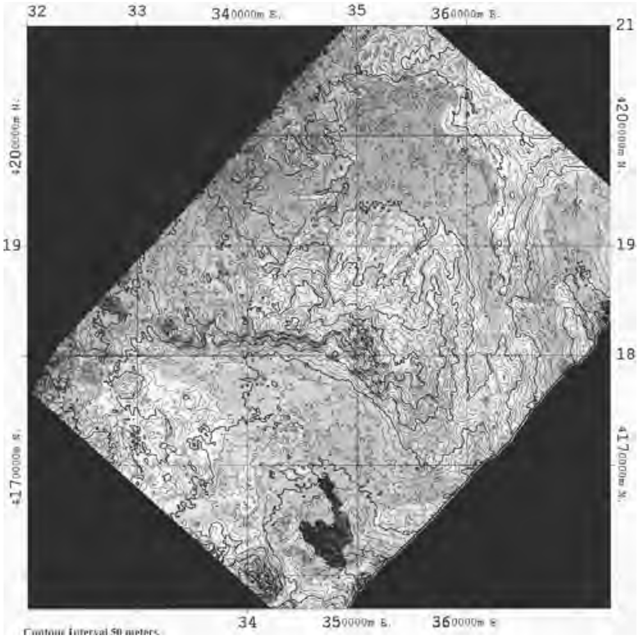
TOPOGRAPHY AND TOPOGRAPHIC MAPS

Topography is the physical shape of the land, particularly as it relates to elevation. Topographic maps are two-dimensional graphical representations of the three-dimensional topography that also provide a detailed and accurate inventory of what exists on the land surface, such as geographic and cultural features.

Topographic maps are distinguished from other maps in their representation of elevation as contour lines. Contour lines are drawn to match the shape of physical features and successive contour lines represent ascending or descending elevations. This allows a user to quickly discern the shape of any landform, determine its elevation, and estimate the rate of elevation changes. For example, a round hill would appear as a series of concentric closed loops that become successively smaller with increased elevation. The closer the contour lines are to one another, the steeper the slope.

In addition to contoured elevations, topographic maps show many other features of the land, including names of natural features such as mountains, valleys, plains, **lakes**, and **rivers**. They identify the amount of vegetative cover and include constructed features like minor and major roads, transmission lines, and buildings. Topographic maps also show political boundaries, survey markers, and different map coordinate systems such as **latitude and longitude**.

The value of topographic maps is in their accuracy and consistency. Topographic maps are based on a rigorous geodesic base, which defines the shape of Earth over a given land **area**. This ensures that all included features will be shown in the exact position. All features on the maps conform to a consistent set of map symbols, allowing comparison of topographic maps from anywhere in the country.



Topographic map made with Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar imaging from Space Shuttle Endeavour, near Long Valley, California. © *Corbis. Reproduced by permission.*

The high accuracy and range of information of topographic maps makes them useful to professional and recreational map users alike. Topographic maps are used for outdoor activities like hiking, camping, and fishing and in professional fields such as engineering, energy exploration, natural resource conservation, environmental management, public works design, commercial and residential planning.

To meet the needs of various users, the United States Geological Survey produces topographic maps at different scales for the entire United States. The scale is the ratio of a unit of measurement on the ground to that on a map. For example, if one inch on a topographic map equals one mile (or 63,360 inches) on the ground, the scale of the map is 1:63,360. The most common scale for topographic maps is 1:24,000, where one map inch equals 2000 feet on the ground. This size map is called a 7.5-minute quadrangle because it covers 7.5 minutes of **latitude** by 7.5 minutes of **longitude**. Maps at this scale are very detailed. A map with a larger ratio, such as 1:100,000 will cover more area but show less detail.

See also Cartography; Relief

TORINO SCALE

Advanced by Massachusetts Institute of Technology Professor Richard P. Binzel in 1995, the Torino scale is a revision of the Near-Earth Object Hazard Index. In 1999, the International Conference on Near-Earth objects adopted the scale at a meeting in *Turino* (Turin), Italy (from which the name of the scale is derived). The Torino scale is used to portray the threat to Earth of an impact with a particular comet or asteroid. The measurement scale is based upon agreement between scholars as a means to categorize potential hazards.

When a new comet or asteroid is initially tracked, an extrapolation of its projected orbital path is compared to predicted Earth orbital positions. The Torino scale assigns categories to the closeness with which an object will approach or cross Earth orbit. Because initial estimates can be greatly altered by refined data regarding the track of an asteroid or comet, it is possible that a particular asteroid or comet could be upgraded or downgraded with regard to the threat it poses Earth. In addition, a different scale designation can be made for each successive orbital encounter over a number of years or decades. Data is most accurate as related to encounters in the near-term because various gravitational forces and encounters with other celestial objects can alter the course of **asteroids** or **comets**.

The Torino scale is based upon a zero to 10 numbering system wherein a zero designates a statistically negligible threat of collision with Earth. At the other extreme, a numerical designation of ten would indicate certain impact. In addition to being based upon the probability of impact, scale numbers also incorporate a potential “damage” value. For example, a very small object with little chance of surviving a fiery entry into Earth’s atmosphere will still be assigned a very low number (zero for very small objects) even if an impact was certain. At the other extreme, the designation 10 carries the ominous distinction of being reserved for a certain impact of cataclysmic proportions.

The size of an object is important because the force (kinetic energy) that it would carry in a collision with Earth is related to its mass and velocity. Like nuclear explosions, estimates of the energy of collision are given in units of megatons (MT).

The Torino scale also assigns colors to the potential hazard assessment. A “white” label means that the asteroid or comet poses no threat (i.e, will miss or not survive entry into the Earth’s atmosphere). Green events designate orbital crossings with a small chance of collision. Yellow events designate more potential orbital crossings than average. A yellow designation would focus intense scientific scrutiny upon the track of the asteroid or comet. Orange events are “threatening” crossings or other encounters with asteroids or comets that have a potential to cause severe destruction. The designation is reserved for objects with a significantly higher risk of impact. Red events or collisions are certain and globally devastating.

Because risk assessments are difficult to quantify, another scale, the Palermo Technical Scale, is often used by astronomers to complement the Torino scale. The Palermo scale offers a more mathematical calculation utilizing the variables of probability of impact and energy of collision.

As of May 2002, with approximately 25% of Near Earth objects identified, no object rating more than a “1” on the Torino scale has yet been detected. For example, during February 2002, an asteroid designated 2002 CU11 was classified as a “1” on the Torino scale (a “green” code). Extrapolations of the orbital dynamics of the asteroid and Earth indicated a low probability (approximately 1 in 9000) of a potential collision in 2049.

As of May 2002, additional information regarding the Torino scale and up-to-date information on identified NEO (Near Earth objects) can be found at the Near Earth Objects Dynamic Site (NEODyS) (<http://newton.dm.unipi.it/neodys/>).

See also Astronomy; Barringer meteor crater; Catastrophism; Gravity and the gravitational field; Hubble Space Telescope (HST); Solar system, Space and planetary geology

TORNADO

A tornado is a rapidly spinning column of air formed in severe thunderstorms. The rotating column, or vortex, forms inside the storm cloud and grows downward until it touches the ground. Although a tornado is not as large as its parent thunderstorm, it is capable of extreme damage because it packs very high **wind** speeds into a compact **area**. Tornadoes have been known to shatter buildings, drive straws through solid wood, lift locomotives from their tracks, and pull the **water** out of small streams. Due to a combination of geography and **meteorology**, the United States experiences most of the world's tornadoes. An average of 800 tornadoes strike the United States each year. Based on statistics kept since 1953, Texas, Oklahoma, and Kansas are the top three tornado states. Tornadoes are responsible for about 80 deaths, 1500 injuries, and many millions of dollars in property damage annually. While it is still impossible to predict exactly when and where tornadoes will strike, progress has been made in predicting tornado development and detecting tornadoes with Doppler radar.

Most tornadoes form in the Northern Hemisphere during the months of March through June. These are months when conditions are right for the development of severe thunderstorms. To understand why tornadoes form, consider the formation and growth of a thunderstorm. Thunderstorms are most likely to develop when the atmosphere is unstable, that is, when atmospheric **temperature** drops rapidly with height. Under unstable conditions, air near the surface that begins rising will expand and cool, but remains warmer (and less dense) than its surroundings. The rising air acts like a hot air balloon; because it is less dense than the surrounding air, it continues to rise. At some point, the rising air cools to the **dew point** where the water vapor in the air condenses to form liquid water droplets. The rising column of air is now a visible cloud. If the rising air, or updraft, is sustained long enough, water droplets will begin to fall out of the rising air column, making it a rain cloud.

This cloud will become a severe storm capable of producing tornadoes only under certain circumstances. Severe storms are often associated with a very unstable atmosphere and moving low-pressure systems that bring cold air into contact with warmer, more humid air masses. Such **weather** situations commonly occur in the eastern and Midwestern United States during the spring and summer months. Large-scale weather systems often sweep moist warm air from the **Gulf of Mexico** over these regions in a layer 1.2–1.9 mi (2–3 km) deep. At the same time, winds aloft (above about 2.5 mi [4 km] in altitude) from the southwest bring cool dry air over the region. Cool air overlying humid air creates very unstable atmospheric conditions and sets the stage for the growth of strong thunderstorms.

The warm surface air is separated from colder air lying farther north by a fairly sharp temperature boundary called a front. A low-pressure center near Earth's surface causes the cold air to advance into the warmer air. The edge of the advancing cold air, called a cold front, forces the warmer air ahead of the front to rise and cool. Because the atmosphere is unstable, the displaced air keeps rising and a cloud quickly forms. Rain that begins to fall from the cloud causes downdrafts (sinking air) in the rear of the cloud. Meanwhile the advancing edge of the storm has strong updrafts and humid air is pulled into the storm. The water vapor in this air condenses to form more water droplets as it rises and cools. When water vapor condenses, it releases latent heat. This warms the air and forces it to rise more vigorously, strengthening the storm.

The exact mechanism of tornado formation inside severe thunderstorms is still a matter of dispute, but it appears that tornadoes grow in a similar fashion to the small vortices that form in draining bathtubs. Tornadoes appear to be upside down versions of this phenomenon. As updrafts in a severe thunderstorm cloud get stronger, more air is pulled into the base of the cloud to replace the rising air. Some of this air may be rotating slightly since the air around the base of a thunderstorm usually contains some **rotation**, or vorticity. As the air converges into a smaller area, it begins to rotate faster due to a law of **physics** known as the conservation of angular momentum. This effect can be seen when an **ice** skater begins spinning with arms outstretched. As the skater brings his or her arms inward, his or her rotational speed increases. In the same way, air moving into a severe storm begins to move in a tighter column and increases its rotational speed. A wide vortex is created, called the mesocyclone. The mesocyclone begins to build vertically, extending itself upward throughout the entire height of the cloud. The rapid air movement causes the surrounding air pressure to drop, pulling more air into the growing vortex. The lowered pressure causes the incoming air to cool quickly and form cloud droplets before they rise to the cloud base. This forms the wall cloud, a curtain-shaped cloud that is often seen before a tornado forms. The mesocyclone continues to contract while growing from the base of the storm cloud all the way up to 6.2 mi (10 km) above the surface. When the mesocyclone dips below the wall cloud, it is called a funnel cloud because of its distinctive funnel shape. This storm is on its way to producing a tornado.

A funnel cloud may form in a severe storm and never reach the ground. If and when it does, the funnel officially becomes a tornado. The central vortex of a tornado is typically about 328.1 ft (100 m) in diameter. Wind speeds in the vortex have been measured at greater than 220 mph (138 km/h). These high winds make incredible feats of destruction possible. They also cause the air pressure in the tornado to drop below normal **atmospheric pressure** by over 100 millibars (the normal day-to-day pressure variations we experience are about 15 millibars). The air around the vortex is pulled into this low-pressure zone where it expands and cools rapidly.

Tornadoes are classified according to their wind speed, which can be estimated by examining the damage they produce. ***AP/Wide World. Reproduced by permission.***

This causes water droplets to condense from the air, making the outlines of the vortex visible as the characteristic funnel-shaped cloud. The low pressure inside the vortex picks up debris such as **soil** particles, which may give the tornado an ominous dark color. The damage path of a tornado may range from 900 ft (275 m) to over 0.5 mi (1 km) wide.

Tornadoes move with the thunderstorm that they are attached to, traveling at average speeds of about 10–30 mph (15–45 kph), although some tornadoes have been seen to stand still, while other tornadoes have been clocked at 60 mph (90 kph). Because a typical tornado has a lifetime of about 5–10 minutes, it may stay on the ground for 5–10 miles. Occasionally, a severe tornado may cut a path of destruction over 200 mi (320 km) long. Witnesses to an approaching tornado often describe a loud roaring noise made by the storm similar to jet engines at takeoff.

The destructive path of tornadoes appears random. One house may be flattened while its neighbor remains untouched. This has been explained by the tornado skipping or lifting up off the surface briefly and then descending again to resume its destructive path. Studies made of these destructive paths after the storm suggest another possible explanation; some tornadoes may have two to three smaller tornado-like vortices circling around the main vortex. According to this theory, these suction vortices may be responsible for much of the actual damage associated with tornadoes. As they rotate around the main tornado core, they may hit or miss objects directly in the tornado's path depending on their position. The tornado's skipping behavior is still not completely understood.

When houses or other structures are destroyed by a tornado, they are not simply blown down by the high winds; they appear to explode. High wind passing over a house roof acts like the air moving over an airplane wing: it gives the roof an upward force or lift, which tends to raise the roof vertically off the house. Winds also enter the building through broken windows or doors pressurizing the house as one would blow up a balloon. The combination of these forces tends to blow the walls and roof off the structure from the inside out, giving the appearance of an explosion.

Tornado strength is classified by the Fujita scale, which uses a scale of one to six to denote tornado wind speed. Since direct measurements of the vortex are not possible, the observed destruction of the storm is used to estimate its "F scale" rating.

The single most violent tornado in United States history was the Tri-State tornado on March 18, 1925. Beginning in Missouri, the tornado stayed on the ground for over 220 mi (350 km), crossing Illinois, moving into Indiana, and leaving a trail of damage over 1 mi (1.6 km) wide in places. Tornado damage often is limited since they usually strike unpopulated areas, but the Tri-State tornado plowed through nine towns and destroyed thousands of homes. When the storm was over, 689 people had lost their lives and over 2,000 were injured, making the Tri-State the deadliest tornado on record.

On May 3, 1999, a storm started in southwestern Oklahoma, near the town of Lawton. By late in the day, it had grown into a violent storm system with 76 reported tornadoes. As the storm system tore across central Oklahoma and into Kansas, over 43 people were killed, over 500 injured and more than 1,500 buildings were destroyed. One of the tornadoes, classed as a F-5, was as much as a mile wide at times and stayed on the ground for over four hours.

The precise tracking and prediction of tornadoes is not yet a reality. Meteorologists can identify conditions that are likely to lead to severe storms. They can issue warnings when atmospheric conditions are right for the development of tornadoes. They can use radar to track the path of thunderstorms that might produce tornadoes. It is still not possible, however, to detect a funnel cloud by radar and predict its path, touchdown point, and other important details. Much progress has recently been made in the detection of tornadoes using Doppler radar.

Doppler radar can measure not just the distance to an object, but also its velocity by using the Doppler effect: if an object is moving toward an observer, radar waves bounced off the object will have a higher frequency than if the object were moving away. This effect can be demonstrated with sound waves. If a car is approaching with its horn sounding, the pitch of the horn (that is, the frequency of the sound waves) seems to rise. It reaches a peak just as the car passes, then falls as the car speeds away from the listener.

Doppler radar is used to detect the motion of raindrops and hail in a thunderstorm, which gives an indication of the motion of the winds. With present technology, it is possible to detect the overall storm circulation and even a developing mesocyclone. The relatively small size of most tornadoes makes direct detection difficult with the current generation of Doppler radar. In addition, any radar is limited by the curvature of Earth. Radar waves go in straight lines, which means distant storms that are below the horizon from the radar cannot be probed with this technique.

See also Atmospheric pressure; Clouds and cloud types; Weather forecasting; Weather forecasting methods; Weather radar; Weather satellite

TORRICELLI, EVANGELISTA (1608-1647)

Italian physicist

As a scientist, Evangelista Torricelli became well known for his study of the motion of fluids, and was declared the father of hydrodynamics by Ernst Mach. Torricelli also conducted experiments on gases, though the term was not then in use. Most notably, Torricelli settled an argument about the nature of gases and the existence of the vacuum. Aristotle believed that a vacuum could not exist. Though Galileo disagreed, he contended that the action of suction (in a **water** pump, for example) was produced by a vacuum itself and not by the pressure of the air pushing on the liquid being pumped. Despite his argument, Torricelli noticed that water could be pumped only a finite distance through a vertical tube before it ceased to move any further and set out to examine this paradox, inventing the first barometer in the process.

During his experimentation, Torricelli filled a one-ended **glass** tube with mercury, then immersed the open end in a dish of more mercury, placing the tube in a upright position. He found that about 30 in (76 cm) of mercury remained in the tube, deducing that a vacuum had been created above the mercury in the tube, and that the mercury was held in place not by the vacuum, but by the pressure of air pushing down the mercury in the dish. Thus, he demonstrated the existence of a vacuum, showed why pumps then in use could only move liquids vertically a certain distance (the distance determined by the pressure of the surrounding air), and created an instrument capable of measuring air pressure.

Torricelli's invention of the barometer led to a burst of both theoretical and experimental work in **physics** and **meteorology**. Torricelli also made a contribution to meteorology with his suggestion that **wind** was not caused by the "exhalations" of vapors from a damp Earth, but by differences in the density of air that, in turn, were caused by differences in the air **temperature**.

Born near Ravenna, Italy, Torricelli was first educated in local Jesuit schools and showed such brilliance that he was sent to Rome to study with Galileo's former student Benedetto Castelli (1578–1643). Through Castelli he first corresponded with and met Galileo, finally becoming his secretary and assistant. A few months after Galileo's death in 1642, Torricelli accepted Galileo's old position as court mathematician and philosopher to the Grand Duke of Tuscany, a position he held until his own death, before his fortieth birthday.

Torricelli's investigations in mathematics played an important role in scientific history as well. Based on Francesco Cavalieri's "geometry of indivisibles," Torricelli worked out equations upon curves, solids, and their rotations, helping to bridge the gap between Greek geometry and calculus. Along with the work of René Descartes, Pierre de Fermat, Gilles Personne de Roberval, and others, these works enabled Isaac Newton and Gottfried Wilhelm Leibniz to give calculus its first complete formulation.

See also Atmospheric pressure

TRADE WINDS • *see* ATMOSPHERIC CIRCULATION

TRANSFORM FAULTS

Transform faults are a special class of faults first described by the Canadian geologist-geophysicist **J. Tuzo Wilson** in 1965 as faults that terminate abruptly at both ends and link one tectonic feature with another. Transform faults that offset mid-oceanic ridges (ridge-ridge transforms) transfer spreading from one segment of the ridge to the next. An important feature of ridge-ridge transform faults is that the sense of displacement along the transform fault is opposite to the sense of offset of the spreading ridge. The length of the active section of the fault remains constant with time. Fracture zones, across which there is no lateral displacement, continue beyond transform faults. Vertical bathymetric offsets occur across transform faults and fracture zones as young, hotter, and hence higher seafloor is juxtaposed against older and colder seafloor. Transform faults lie along small circles about a fixed Euler pole of **rotation**, implying a constant direction of plate motion. Volcanism and formation of new oceanic **crust** may occur along divergent or leaky transform faults. Transform faults can also occur between two subduction zones (trench-trench or arc-arc transforms) or between a spreading center and a **subduction zone** (ridge-trench or ridge-arc arc transform).

Faults geometrically equivalent to transform faults exist at the outcrop scale, especially in **limestone** and **marble**. Faults that offset two extension fracture veins may form in an equivalent manner to ridge-ridge transforms. Again, the sense of vein offset is opposite to the sense of displacement along the fault. Faults between two domains in which material is lost due to pressure solution (forming stylolites) are geometrically equivalent to arc-arc transforms. Faults between extensional veins and stylolites (on the same side of the fault) show an equivalent geometry to ridge-arc transforms.

See also Faults and fractures; Mid-ocean ridges and rifts; Plate tectonics; Transform plate boundary

TRANSFORM PLATE BOUNDARY

A transform plate boundary is a margin between two **lithospheric plates** that constitutes a regional-scale transform fault. The best-known transform plate boundary is the San Andreas fault system, which accommodates the right-lateral displacement between the North American and Pacific plates. The northwards-moving Pacific plate is subducted at the Aleutian trench and at western Pacific **island arcs**. Western California, part of the Pacific Plate, comprises exotic terranes translated northwards and rotated through angles up to 90 degrees along the margin of the North American plate. In the north, the San Andreas fault system terminates at the Mendocino triple junction where it intersects the Mendocino Fracture Zone and Cascadia subduction. Here the North American and Pacific plates intersect the Gorda–Juan de Fuca plate. The easterly moving Gorda–Juan de Fuca plate is subducted beneath the American plate north of the San Andreas fault system termination forming the Cascade Range. The San Andreas fault system steps through a series of oblique spreading ridges and **transform faults** in the Gulf of California. It terminates at the Rivera triple junction in the southern Gulf of California (junction between the Rivera, Pacific and North American plates). South of this triple junction, the Rivera Plate is subducted beneath **North America**. The San Andreas Fault is the main transcurrent or strike-slip fault within a broad deformation zone that comprises hundreds of minor faults along western California. Changes in their orientation and relay stepping of faults result in localized dilatation or contraction. Some segments of the San Andreas and other major faults in the San Andreas fault system are locked. In such segments, built-up strain may finally be rapidly released, producing an **earthquake**. Other segments are undergoing slow, continuous deformation or **creep**. The **lithosphere** is thinner beneath the San Andreas fault system than for normal continental lithosphere.

The Alpine Fault Zone along the western South Island of New Zealand is an example of an obliquely convergent transform plate boundary separating two zones of subduction with opposite polarity. North of New Zealand, the Pacific Plate is obliquely subducted beneath the Indo-Australian plate at the Tonga-Kermadec trench. South of New Zealand, the Indo-Australian Plate is obliquely subducted beneath the Pacific Plate at the Puysegur Trench. Right-lateral displacement and horizontal shortening occur across a zone 93–125 mi (150–200 km) wide. Most displacement has occurred along the Alpine Fault, which comprises oblique thrusts linked by sub-vertical dextral transcurrent faults.

See also Faults and fractures; Plate tectonics; Subduction zone

TRANSITION ZONE • *see* SEISMOLOGY

TRANSVERSE DUNES • *see* DUNES

TRIASSIC PERIOD

The Triassic Period, first of the **Mesozoic Era's** three periods, began about 240 million years ago and lasted for approximately 40 million years. It was preceded by the great Permian-Triassic mass extinction, which destroyed over 90% of living species. This extinction, the worst in Earth's history, was probably caused in part by the merger (late in the late Permian) of all the continental plates into a single huge land mass, Pangaea (pronounced pan-JEE-ah). This destroyed many species by producing a net loss of coastline, while Pangaea's size—one fourth of the Earth's surface—dictated an arid climate over much of its interior. The Triassic was therefore a period of adaptive radiation—the slow filling of vacant ecological niches by species evolved from survivors of the great extinction.

For the most part Pangaea remained geologically stable and volcanically inactive during the Triassic. **Erosion** proceeded more rapidly than mountain-building. Particles eroded from the Pangaean highlands accumulated in various basins to produce a distinctively Triassic class of reddish sandstones and shales called the red beds. It is not known why the red beds are all red; some geologists argue that the Pangaean climate encouraged iron-concentrating **soil** bacteria. In the late

Triassic, the plates comprising Pangaea began to break up, and continental drift has subsequently distributed the red beds all over the world (**North America**, South **Africa**, **Europe**, Brazil).

Conifers (pine trees) and ferns were common land plants of the Triassic Period. Petrified Triassic conifers, some over 5 ft (1.5 m) across and over 100 ft (30 m) long, are found in Utah.

More than 95% of marine invertebrate species died in the Permian-Triassic extinction. During the Triassic, invertebrates slowly re-evolved diversity. Lobsters and crabs first appeared in this period.

Reptiles increased in number and variety throughout the Triassic Period. Some species took to the sea, evolving into the fish-eating plesiosaurs and *ichthyosaurs*. The first mammals appeared late in the Triassic Period. These were small and shrew-like, as their descendants would remain until the final elimination of the dinosaurs by an asteroid impact some 120 million years later.

The first dinosaurs also evolved in the late Triassic, but remained unspectacular by modern standards. It was not until the **Jurassic Period** that the most familiar species (Tyrannosaurus rex, Brontosaurus, etc.) were to evolve.

See also Archean; Cambrian Period; Carbon dioxide; Cenozoic Era; Continental drift theory; Cretaceous Period; Dating methods; Devonian Period; Eocene Epoch; Evolution, evidence of; Fossil record; Fossils and fossilization; Geologic time; Historical geology; Holocene Epoch; Miocene Epoch; Mississippian Period; Oligocene Epoch; Ordovician Period; Paleocene Epoch; Paleozoic Era; Pennsylvanian Period; Phanerozoic Eon; Pleistocene Epoch; Pliocene Epoch; Precambrian; Proterozoic Era; Quaternary Period; Silurian Period; Tertiary Period

TROPIC OF CANCER • *see* SOLAR ILLUMINATION: SEASONAL AND DIURNAL PATTERNS

TROPIC OF CAPRICORN • *see* SOLAR ILLUMINATION: SEASONAL AND DIURNAL PATTERNS

TROPICAL CYCLONE

Tropical cyclones are large circulating storm systems consisting of multiple bands of intense showers and thunderstorms and extremely high winds. These storm systems develop over warm ocean waters in the tropical regions that lie within about 25° **latitude** of the equator. Tropical cyclones may begin as isolated thunderstorms. If conditions are favorable, they grow and intensify to form the storm systems known as hurricanes in the Americas, typhoons in East **Asia**, willy-willy in **Australia**, cyclones in Australia and India, and baguios in the Philippines. A fully developed tropical cyclone is a circular complex of thunderstorms about 403 mi (650 km) in diameter and over 7.5 mi (12 km) high. Winds near the core of the cyclone can exceed 110 mph (50 meters/second). At the center of the storm is a region about 9–12.5 mi (15–20 km) across called the eye, where the winds are light and skies are often clear. After forming and reaching peak strength over tropical **seas**, tropical cyclones may blow inland, causing significant damage and loss of life. The storm destruction occurs by high winds and forcing rapid rises in sea level that flood low lying coastal areas. Better forecasting and emergency planning has lowered the death tolls in recent years from these powerful storms.

Several ocean areas adjacent to the equator possess all the necessary conditions for forming tropical cyclones. These spots are: the West Indies/Caribbean Sea, where most hurricanes develop between August and November; the Pacific Ocean off the west coast of Mexico, with a peak hurricane season of June through October; the western Pacific/South China Sea, where most typhoons, baguios, and cyclones form between June and December; and south of the equator in the southern Indian Ocean and the south Pacific near Australia, where the peak cyclone months are January to March. Note that in each **area** the peak season is during late summer (in the Southern Hemisphere, summer runs from December to March). Tropical cyclones require warm surface waters at least 80°F (27°C). During the late summer months, sea surface temperatures reach their highest levels and provide tropical cyclones with the energy they need to develop into major storms.

The annual number of tropical cyclones reported varies widely between regions and from year to year. The West Indies recorded 658 tropical cyclones between 1886–1966, an average of about eight per year. Of these, 389, or about five per year, grew to be of hurricane strength. The Atlantic hurricane basin has a 50-year average of ten tropical storms and six hurricanes annually.

In the United States, the National **Weather** Service names hurricanes from an alphabetic list of alternating male and female first names. New lists are drawn up each year to name the hurricanes of western Pacific and the West Indies. Other naming systems are used for the typhoons and cyclones of the eastern Pacific and Indian **oceans**.

In some ways, tropical cyclones are similar to the low pressure systems that cause weather changes at higher latitudes in places like the United States and **Europe**. These systems are called extratropical cyclones and are marked with an "L" on weather maps. These weather systems are large masses of air circulating cyclonically (counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere). Cyclonic circulation is caused by two forces acting on the air: the pressure gradient and the Coriolis force.

In both cyclone types air rises at the center, creating a region of lower air (barometric) pressure. Because air is a fluid, it will rush in from elsewhere to fill the void left by air that is rising off the surface. The effect is the same as when a plug is pulled out of a full bathtub: **water** going down the drain is replaced by water rushing in from other parts of the tub. This is called the pressure gradient force because air moves from regions of high pressure to lower pressure. Pressure gradient forces are responsible for most day-to-day winds. As the air moves toward low pressure, the Coriolis force turns the air to the right of its straight-line motion (when viewed from above). In the Southern Hemisphere, the reverse is true: the Coriolis force pushes the moving air to the left. The air, formerly going straight toward a low-pressure region, is forced to turn away from it. The two forces are in balance when the air circles around the low pressure zone with a constant radius creating a stable cyclone rotating counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

All large-scale air movements such as hurricanes, typhoons, extratropical cyclones, and large thunderstorms set up a cyclonic circulation in this manner. (Smaller scale circulations such as the vortex that forms in a bathtub drain are not cyclonic because the Coriolis force is overwhelmed by other forces. The larger a system, the more likely that the Coriolis force will prevail and the **rotation** will be cyclonic.) The Coriolis force is a consequence of the rotation of Earth. Moving air masses, like any other physical body, tend to move in a straight line. However, we observe them moving over Earth's surface, which is rotating underneath the moving air. From our perspective, the air appears to be turning even though it is actually going in a straight line, and it is we who are moving.

In both tropical and extratropical cyclones, the rising air at the cyclone center causes **clouds** and **precipitation** to form. A fully developed hurricane consists of bands of thunderstorms that grow larger and more intense as they move closer to the cyclone center. The area of strongest updrafts can be found along the inner wall of the hurricane. Inside this inner wall lies the eye, a region where air is descending. Descending air is associated with clearing skies; therefore, in the eye the torrential rain of the hurricane ends, the skies clear, and winds drop to nearly calm. In the eye of a hurricane, the eye wall clouds appear as towering vertical walls of thunderstorm clouds, stretching up to 7.5 mi (12 km) in height, and usually completely surrounding the eye. Hurricanes and other tropical cyclones move at the speed of the prevailing winds, typically 10–20 mph (16–32 kph) in the tropics. A hurricane eye passes over an observer in less than an hour, replaced by the high winds and heavy rain of the intense inner thunderstorms.

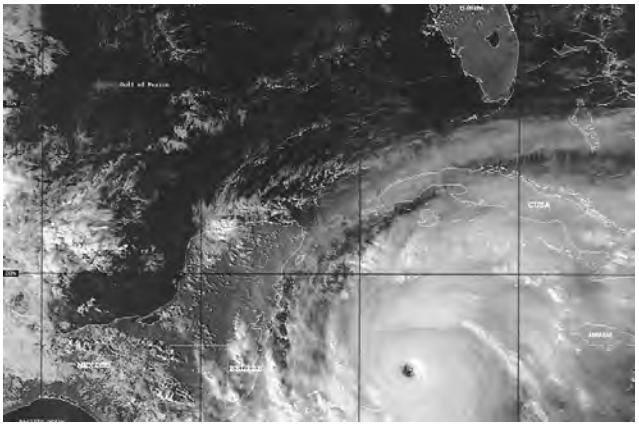
Several conditions are necessary to create a tropical cyclone. Warm sea surface temperatures, which reach a peak in late summer, are required to create and maintain the warm, humid air mass in which tropical cyclones grow. This provides energy for storm development through the heat stored in humid air, called latent heat. It takes energy to change water into vapor; that is why one must add heat to boil a kettle of water. The reverse is also true: when vapor condenses back to form liquid water, heat is released that may heat up the surrounding air. In a storm such as a hurricane, many hundreds of tons of humid air are forced to rise and cool, condensing out tons of water droplets and liberating a vast quantity of heat. This warms the surrounding air, causing it to expand and become even more buoyant, that is, more like a hot air balloon. More air begins rising, causing even more humid air to be drawn into the cyclone. This process feeds on itself until it forms a cyclonic storm of huge proportions. The more humid air available to a tropical cyclone, the greater its upward growth and the more intense it will become.

For storm growth to begin, air needs to rise. Because tropical air masses are uniformly warm and humid, the atmosphere over much of the tropics is stable; that is, it does not support rising air and the development of storms. Thunderstorms occasionally develop but tend to be short-lived and small in scale, unlike the severe thunderstorms in the middle latitudes. During the late summer, this peaceful picture changes. Tropical disturbances begin to appear. These can take the form of a cluster of particularly strong thunderstorms or perhaps a storm system moving westward off of the African continent and out to sea. Tropical disturbances are regions of lower pressure at the surface. As we have seen, this can lead to air rushing into the low pressure zone and setting up a vortex, or rotating air column, with rising air at its core.

An additional element is needed for tropical cyclone development: a constant **wind** direction with height throughout the lower atmosphere. This allows the growing vortex to stretch upward throughout the atmosphere without being sheared apart. Even with all these elements present, only a few of the many tropical disturbances observed each year become hurricanes or typhoons. When a tropical disturbance near the surface encounters a similar disturbance in the air flow at higher levels such as a region of low pressure at about the 3 mi (5 km) level (called an upper low), conditions are favorable for hurricane formation. These upper lows sometimes wander toward the equator from higher latitudes where they were part of a decaying weather system.

Once a tropical disturbance has begun to intensify, a chain reaction occurs. The disturbance draws in humid air and begins rising. Eventually it condenses to form water droplets. This releases latent heat, which warms the air, making it less dense and more buoyant. The air rises more quickly from the surface. As a result, the pressure in the disturbance drops and more humid air moves toward the storm. Meanwhile, the disturbance starts its cyclonic rotation and surface winds begin to increase. Soon, the tropical disturbance forms a circular ring of low air pressure and becomes known as a tropical depression. As more heat energy is liberated and updrafts increase inside the vortex, the internal barometric pressure continues to drop and the incoming winds increase. When wind speeds increase beyond 37 mph (60 kph), the depression is upgraded to a tropical storm. If the winds reach 75 mph (120 kph), the tropical storm is officially classified as a hurricane (or typhoon, cyclone, etc., depending on location). The chain reaction driving this storm growth is efficient. About 50–70% of tropical storms intensify to hurricanes.

A mature tropical cyclone is a giant low-pressure system pulling in humid air, releasing its heat, and transforming it into powerful winds. The storm can range in diameter from 60–600 mi (100–1000 km) with wind speeds greater than 200 mph (320 kph). The central barometric pressure of the hurricane drops 60 millibars (mb) below the normal sea level pressure of 1013 mb. By comparison, the passage of a strong storm front in the middle latitudes may cause a drop of about 20–30 mb. The size and strength of the storm is limited only by the air's **humidity**, which is determined by ocean **temperature**. It is estimated that for every 1.8°F (1°C) increase in sea surface temperature, the central pressure of a tropical cyclone can drop 12 mb. With such low central pressure, winds are directed inward, but near the center of the storm the winds are rotating so rapidly the Coriolis force prevents any further inward movement. This inner boundary creates the eye of the tropical cyclone. Unable to go in, the air is forced to move upward and then



Satellite photo of Hurricane Mitch. ***National Oceanic and Atmospheric Administration (NOAA).***

spread out at an altitude of about 7.5 mi (12 km). Viewed from above by a **satellite**, the tropical cyclone appears as a mass of clouds diverging away from the central eye.

All of the cyclone development described thus far takes place at sea, but the entire cyclone also is blown along with the prevailing winds. Often this movement brings the storm toward land. As tropical cyclones approach land, they begin affecting the coastal areas with sea swells, large waves caused by the storm's high winds. Swells often reach 33 ft (10 m) in height and can travel thousands of kilometers from the storm. Coastal areas are at risk of severe damage from these swells that destroy piers, beach houses, and harbor structures every hurricane season. Particularly high swells may cause flooding farther inland.

More dangerous than the gradually rising swells are the sudden rises in sea level known as storm surges. Storm surges occur when the low barometric pressure near the center of a cyclone causes the water surface below to rise. Then strong winds blowing toward the coast push this "bulge" of water out ahead of the storm. The water piles up against the coast, quickly raising sea level as much as 16 ft (5 m) or more. The highest storm surge (for Northern Hemisphere storms, hurricanes) generally occurs east of the storm's path. When storm-tossed waves of 23–33 ft (7–10 m) are added to this wall of water, land areas may be inundated. In 1900, the city of Galveston, Texas, was hit with a destructive storm surge during a hurricane. One eyewitness reported that the sea rose 4 ft (1.3 m) in a matter of seconds. Over 5,000 people lost their lives in the Galveston hurricane and resulting flooding, making it the deadliest storm ever recorded in the United States.

Tropical cyclones that travel onto the land immediately begin to weaken as humid air, their source of energy, is cut off. The winds at the base of the cyclone encounter greater friction as they drag across uneven terrain that slows them. Nevertheless, tropical cyclones at this stage are still capable of producing heavy rains, thunderstorms, and even tornadoes. Occasionally, the remnants of a tropical cyclone that has begun to weaken over land will unite with an extratropical low pressure system, forming a potent rain-making storm front that may bring flooding to areas far from the coast.

Until relatively recently, people in the path of a tropical cyclone had little warning of approaching storms. Usually their only warning signs were the appearance of high clouds and a gradual increase in winds. Hurricane watch services were established beginning in the early years of the twentieth century. By the 1930s, hurricanes were detected with weather balloons and ship reports while the 1940s saw the introduction of airplanes as hurricane spotters. Radar became available after World War II and has remained a powerful tool for storm detection. Today, a global network of weather satellites allows meteorologists to identify and track tropical cyclones from their earliest appearance as disturbances over the remote ocean. This improved ability to watch storms develop anywhere in the world has meant that warnings and evacuation orders can be issued well in advance of a tropical cyclone reaching land. Even though coastal areas have more people living near them today than ever before and tropical cyclones remain as powerful as ever, fewer storm-related deaths are now reported due to advances in storm detection and forecasting.

See also Air masses and fronts; Atmospheric pressure; Beach and shoreline dynamics; Beaufort wind scale; Convection (updrafts and downdrafts); El Nino and La Nina phenomena; Meteorology; Ocean circulation and currents; Wave motions; Weather forecasting methods; Weather forecasting; Weather radar; Weather satellite

TROPOSPHERE AND TROPOPAUSE

The troposphere is the lowest and thickest layer of the atmosphere. In contact with Earth's surface, the troposphere is heated by solar illumination and conduction. The tropopause is the boundary layer between the troposphere and the **stratosphere**.

The thickness of the troposphere depends upon a number of atmospheric variables at **latitude**. The troposphere ranges from a thickness of approximately 5.5 mi (9 km) in the polar regions, to a thickness of approximately 10 mi (16 km) in equatorial regions.

Although the troposphere contains more than 70% of Earth's atmosphere by weight, it is much thinner than the stratosphere or **ionosphere**. Because density increases with increasing mass, the troposphere exhibits a high pressure and density gradient wherein density and pressure decrease with increasing altitude.

Weather phenomena (e.g., rain, snow, etc.) take place in the troposphere. Convective currents provide mixing of air masses with different temperatures. These currents pass through regions of the troposphere that differ widely in pressure. The troposphere **atmospheric pressure** gradient varies by approximately 90% from sea level pressures to tropopause atmospheric pressures.

Under normal atmospheric conditions, the standard lapse rate describes decreasing temperatures encountered with increased altitude within the troposphere. The standard **temperature** lapse rate means that temperature decreases with altitude at a fairly uniform rate. Because the atmosphere is warmed by conduction from Earth's surface, this lapse or reduction in temperature is normal with increasing distance from the conductive source. The tropopause is specifically defined as that upper boundary layer of the troposphere where the thermal lapse rate no longer exists and temperature exhibit stability prior to increasing within the stratosphere.

The bulk of tropospheric heating occurs via conduction of heat from the surface. Differing amounts of sunlight (differential levels of solar **insolation**) result in differential temperatures at the interface between Earth's surface and the troposphere. Warmer surface temperatures and higher rates of conduction allow warm air to create low-pressure zones where air is uplifted. Because surrounding air must rush in to replace the uplifted air, these warmer areas become zones of convergence (inward rushing air). Cooler surface temperatures and lower rates of conduction result in cooler, denser, higher pressure areas that form zones of divergence in which air moves outwards from the high pressure **area**.

The thermal instability means that the troposphere is the turbulent thermal boundary layer of Earth's atmosphere. In contrast to the unstable and vertical currents encountered in the humid troposphere, the stratosphere exhibits a near laminar (horizontal or sheet-like) flow.

See also Air masses and fronts; Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric pollution; Atmospheric pressure; Weather forecasting methods; Wind chill; Wind shear; Wind

TSUNAMI

Tsunami, or seismic sea waves, are a series of very long wavelength ocean waves generated by the sudden displacement of large volumes of **water**. The generation of tsunami waves is similar to the effect of dropping a solid object, such as a stone, into a pool of water. Waves ripple out from where the stone entered, and thus displaced, the water. In a tsunami, the "stone" comes from underneath the ocean or very close to shore, and the waves, usually only three or four, are spaced about 15 minutes apart.

Tsunami can be caused by underwater (submarine) earthquakes, submarine **volcanic eruptions**, falling (slumping) of large volumes of ocean sediment, coastal landslides, or even by meteor impacts. All of these events cause some sort of landmass to enter the ocean and the ocean adjusts itself to accommodate this new mass. This adjustment creates the tsunami, which can circle around the world. Tsunami is a Japanese word meaning "large waves in harbors." It can be used in the singular or plural sense. Tsunami are sometimes mistakenly called tidal waves, but scientists avoid using that term since they are not at all related to **tides**.

Tsunami are classified by oceanographers as shallow water surface waves. Surface waves exist only on the surface of liquids. Shallow water waves are defined as surface waves occurring in water depths that are less than one half their wavelength. Wavelength is the distance between two adjacent crests (tops) or troughs (bottoms) of the wave. Wave height is the vertical distance from the top of a crest to the bottom of the adjacent trough. Tsunami have wave heights that are very small as compared to their wavelengths. In fact, no matter how deep the water, a tsunami will always be a shallow water wave because its wavelength (up to 150 mi [240 km]) is so much greater than its wave height (usually no more than 65 ft [20 m]).

Shallow water waves are different from deep water waves because their speed is controlled only by water depth. In the open ocean, tsunami travel quickly (up to 470 mph [760 kph]), but because of their low height (typically less than 3 ft [1 m]) and long wavelength, ships rarely notice them as they pass underneath. However, when a tsunami moves into shore, its speed and wavelength decrease due to the increasing friction caused by the shallow sea floor.

Wave energy must be redistributed, however, so wave height increases, just as the height of small waves increases as they approach the beach and eventually break. The increasing tsunami wave height produces a "wall" of water that, if high enough, can be incredibly destructive. Some tsunami are reportedly up to 200 ft (65 m) tall. The impact of such a tsunami can range miles inland if the land is relatively flat.

Tsunami may occur along any shoreline and are affected by local conditions such as the coastline shape, ocean floor characteristics, and the nature of the waves and tides already in the **area**. These local conditions can create substantial differences in the size and impact of the tsunami waves, even in areas that are very close geographically.

Tsunami researchers classify tsunami according to their area of effect. They can be local, regional, or ocean-wide. Local tsunami are often caused by submarine volcanoes, submarine sediment slumping, or coastal landslides. These can often be the most dangerous because there is often little warning between the triggering event and the arrival of the tsunami.

Seventy-five percent of tsunami are considered regional events. Japan, Hawaii, and Alaska are commonly hit by regional tsunami. Hawaii, for example, has been hit repeatedly during this century, about every 5–10 years. One of the worst was the April 1, 1946, tsunami that destroyed the city of Hilo.

Pacific-wide tsunami are the least common as only 3.5% of tsunami are this large, but they can cause tremendous destruction due to the massive size of the waves. In 1940 and 1960, destructive Pacific-wide tsunami occurred. More recently, there was a Pacific-wide tsunami on October 4, 1994, which caused substantial damage in Japan with 11.5 ft (3.5 m) waves. However, waves of only 6 in (15 cm) over the normal height were recorded in British Columbia.

Tsunami are not only a modern phenomenon. The decline of the Minoan civilization is believed to have been triggered by a powerful tsunami that hit the area in 1480 B.C. and destroyed its coastal settlements. Japan has had 65 destructive tsunami between A.D. 684 and 1960. Chile was hit in 1562 and Hawaii has a written history of tsunami since 1821. The Indian and Atlantic **Oceans** also have long tsunami histories. Researchers are concerned that the impact of future tsunami, as well as hurricanes, will be worse because of intensive development of coastal areas in the last 30 years.

Tsunami inundating Hilo, Hawaii. ***National Oceanic and Atmospheric Administration (NOAA).***

The destructive 1946 tsunami at Hilo, Hawaii, caused researchers to think about the problem of tsunami prediction. It became clear that if scientists could predict when the waves are going to hit, steps could be taken to minimize the impact of the great waves.

In 1965, the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific, and Cultural Organization agreed to expand the United States' existing tsunami warning center at Ewa Beach, Hawaii. This marked the formation of the Pacific Tsunami Warning Center (PTWC), which is now operated under the U.S. **Weather** Service. The objectives of the PTWC are to "detect and locate major earthquakes in the Pacific basin; determine whether or not tsunami have been generated; and to provide timely and effective information and warnings to minimize tsunami effects."

The PTWC is the administrative center for all the associated centers, committees, and commissions of the International Tsunami Warning System (ITWS). Japan, the Russian Federation, and Canada also have tsunami warning systems and centers and they coordinate with the PTWC. In total, 27 countries now belong to the ITWS.

The ITWS is based on a world-wide network of seismic and tidal data and information dissemination stations, and specially trained people. Seismic stations measure movement of the earth's **crust** and are the foundation of the system. These stations indicate that some disturbance has occurred that may be powerful enough to generate tsunami. To confirm the tsunami following a seismic event, there are specially trained people called tide observers with monitoring equipment that enables them to detect differences in the wave patterns of the ocean. Pressure gauges deployed on the ocean can detect changes of less than 0.4 in (1 cm) in the height of the ocean, which indicates wave height. Also, there are accelerometers set inside moored buoys that measure the rise and fall of the ocean, which will indicate the wave speed. These data are used together to help researchers confirm that a tsunami has been generated. Tsunami can also be detected by **satellite** monitoring methods such as radar and photographic images.

The ITWS is activated when earthquakes greater than 6.75 on the **Richter scale** are detected. The PTWC then collects all the data, determines the magnitude of the quake and its epicenter. Then they wait for the reports from the nearest tide stations and their tide observers. If a tsunami wave is reported, warnings are sent to the information dissemination centers.

The information dissemination centers then coordinate the emergency response plan to minimize the impact of the tsunami. In areas where tsunami frequency is high, such as Japan, the Russian Federation, Alaska, and Hawaii, there are also Regional Warning Systems to coordinate the flow of information. These information dissemination centers then decide whether to issue a "Tsunami Watch," which indicates that a tsunami may occur in the area, or a more serious "Tsunami Warning," which indicates that a tsunami will occur.

The entire coastline of a region is broken down into smaller sections at predetermined locations known as "breakpoints" to allow the emergency personnel to customize the warnings to account for local changes in the behavior of the tsunami. The public is kept informed through local radio broadcasts. If the waves have not hit within two hours of the estimated time of arrival, or, the waves arrived but were not damaging, the tsunami threat is assumed to be over and all Watches and Warnings are canceled.

One of the more recent changes in the ITWS is that the Regional Centers will be taking on greater responsibility for tsunami detection and warning procedures. This is being done because there have been occasions when the warning from Hawaii came after the tsunami hit the area. This can occur with local and regional tsunami that tend to be smaller in their area of effect. Some seismically active areas need to have the warning system and equipment closer than Hawaii if they are to protect their citizens. For example, the Aleutian Islands near Alaska have two to three moderate earthquakes per week. As of May 1995, centers such as the Alaska Tsunami Warning Center located in Palmer, Alaska, have assumed a larger role in the management of tsunami warnings.

In terms of basic research, one of the biggest areas of investigation is the calculation of return rates. Return rates, or recurrence intervals, are the predicted frequency with which tsunami will occur in a given area and are useful information, especially for highly sensitive buildings such as nuclear power stations, offshore oil drilling platforms, and hospitals. The 1929 tsunami in Newfoundland has been studied extensively by North American researchers as a model for return rates and there has been some dispute. Columbia University researchers predict a reoccurrence in Newfoundland in 1,000–35,000 years. However, some geologists argue that it may reoccur as soon as 100–1,000 years. These calculations are based on evidence from mild earthquakes and tsunami in the area. They also suggest that the 1929 tsunami left a sedimentary record that is evident in the **soil** profile, and that such records can be dated and used to calculate return rates. Research is currently ongoing to test this theory.

See also Seismology; Wave motions

TUFA

Tufa belong to a group of crust-like carbonate deposits that are formed through the organically and inorganically controlled **precipitation** of calcium carbonates from fresh **water**. Other members of this group are travertines, sinters, and lacustrine limestones or marl lake deposits. **Cave** deposits of a somewhat similar origin are called flowstones, speleothems (stalagmites and **stalactites**). The terms tufa and travertine have a Latin origin. The first is derived from *tophus* and was used by Pliny to describe porous whitish deposits including volcanic material, which is nowadays called volcanic **tuff**. The term travertine stems from lapis *tiburtinus* or Tibur stone.

The distinction of terms used to describe surface **freshwater** carbonates in the literature is not very clear. However, today the term tufa is usually used to describe the more porous varieties, while travertines are denser and sometimes laminated. Sinters are mostly laminated and lack **porosity**. Lacustrine limestones are hardly compacted.

The porosity in tufas is derived from authochtonous plants such as mosses, green algae or reed, which are encrusted by carbonates. Tufas are typically found as deposits of cool spring waters, which are supersaturated by calcium bicarbonate. The precipitation of carbonates in these meteogene deposits is assisted by photosynthesis of phototrophic microbes and plants. Generally, however, any decrease in the partial pressure of CO_2 will trigger carbonate precipitation.

Travertines, in contrast, are mostly of hydrothermal origin and usually lack **fossils** of macrophytes or invertebrates. The CO_2 in these thermogene deposits can be supplied by various processes including degassing of the upper mantle in areas of tectonic stress. Travertines commonly change to a more porous tufa-fabric in areas where the water has cooled down to near ambient **temperature**.

Tufas and travertines are formed in fluvial environments with a growth rate that can sometimes exceed 0.8 in (2 cm) per year but is seldom smaller than 0.08 in (2 mm) per year. They build up barriers leading to the formation of shallow pools in which carbonate mud is deposited. This succession of barriers and pools can cover wide areas, sometimes miles in length (e.g., Grand **Canyon**, Arizona or Mammoth Hot Springs, Wyoming). Other seemingly related formations such as the deposits of the geysers and hot springs in the Yellowstone National Park (Wyoming) are in fact siliceous sinter.

Tufas and travertines are particularly common in the late Pleistocene. Today, they form under a wide variety of climatic regimes from cool and temperate to semi-arid conditions while the growth of fossil travertines of the Quaternary seems to be restricted to the interstadials and interglacials in high and medium latitudes. Some calcareous fresh water deposits show well-developed laminae that probably mirror seasonal differences in one or more environmental variables (water depth or temperature, detrital input).

See also Stalactites and stalagmites

TUFF

Tuffs are volcanic **igneous rocks** composed mostly of compacted volcanic ash and **sand** (particles less than 0.16 in [4 mm] in diameter). Tuffs often show well-defined layers, recording episodic falls of ash, and may be classified in various ways. First, they are often named according to the types of recognizable **rock** fragments embedded in them (i.e., **basalt** tuff, **andesite** tuff, **rhyolite** tuff, etc.). They may also be classified as vitric, lithic, or crystal; vitric tuffs consist mostly of glassy particles, lithic tuffs of rocky particles, and crystal tuffs of visible **crystals**. Tuff may also be characterized as lapilli tuff or tuff-breccia: lapilli tuff consists of ash mixed with lapilli (volcanic fragments 0.08–2.5 in [2–64 mm] in diameter); tuff-breccia consists of ash mixed with block-sized (volcanic fragments $>$2.5 in [64 mm] diameter) fragments.

Volcanoes lay down tuffs by various processes. First, ash lofted to high altitudes may spread over thousands of square miles of terrain before settling out to produce a relatively thin layer of tuff. Such layers are useful to geologists as marking a specific moment in geological time over a wide region. Second, ash lying on the sides of a **volcano** may become saturated by the torrential rains that often occur in response to **volcanic eruptions** and pour down the cinder cone as a **mud flow**. Third, ash may erupt straight up and spread around the vent as a backfill flow. Fourth, large masses of ash and sand mixed with hot gas can be ejected by a volcano and **avalanche** rapidly down its slopes. Such an avalanche is called a *nuée ardente* (pronounced nie-ay-ar-DAHNT; French for burning cloud). A *nuée ardente* can be carried by its momentum many miles from its source, even traversing mountain ridges to lay down ash in distant valleys. After settling, the heat and weight of the ash deposits left by a *nuée ardente* often weld their particles together, creating the rocks termed welded tuffs.

Tuffs are usually much altered in composition and texture after deposition. Alteration may begin with the stewing of a hot ash layer in its own gasses and condensed fluids, or with the addition of outside **water** to the hot ash. Over geological time, few tuffs escape alteration, especially by devitrification. In devitrification, the chaotically mixed atoms in a tuff's volcanic **glass** (which is inherently unstable in atmospheric conditions) reorganize themselves into crystals.

U

ULTRAMAFIC • *see* PERIDOTITE

ULTRAVIOLET RAYS AND RADIATION

Just like visible light, infrared light, and radio waves, ultraviolet light is electromagnetic radiation. On the spectrum, ultraviolet light lies between violet light and x rays, with wavelengths ranging from four to 400 nanometers. Although it is undetectable to the naked eye, anyone who has been exposed to too much sunlight has probably noted the effects of ultraviolet light, for it is this radiation that causes tanning, sunburn, and can lead to skin cancer.

The man credited with the discovery of ultraviolet light is the German physicist Johann Ritter. Ritter had been experimenting with silver chloride, a chemical known to break down when exposed to sunlight. He found that the light at the blue end of the visible spectrum—blue, indigo, violet—was a much more efficient catalyst for this reaction. Experimenting further, he discovered that silver chloride broke down most efficiently when exposed to radiation just beyond the blues, radiation that was invisible to the eye. He called this new type of radiation ultraviolet, meaning "beyond the violet." While ultraviolet radiation in large doses is hazardous to humans, a certain amount is required by the body. As it strikes the skin, it activates the chemical processes that produce Vitamin D. In areas that lack adequate sunshine, children are sometimes plagued by rickets. In order to treat these cases, or to supplement natural light in sun-starved communities, ultraviolet lamps are often used in place of natural sources.

There are three varieties of ultraviolet lamps, each producing ultraviolet light of a different intensity. Near-ultraviolet lamps are fluorescent lights whose visible light has been blocked, releasing ultraviolet radiation just beyond the visible spectrum. These lamps are also known as black lights, and are primarily used to make fluorescent paints and dyes "glow" in the dark. This effect is often seen in entertainment, but can also be used by industry to detect flaws in machine parts.

Middle-ultraviolet lamps produce radiation of a slightly shorter wavelength. They generally employ an excited arc of mercury vapor and a specially designed **glass** bulb. Because middle-ultraviolet radiation is very similar to that produced by the **Sun**, these lamps are frequently used as sunlamps and are often found in tanning salons and greenhouses. Photochemical lamps generating middle-ultraviolet light are also used in industry, as well as by chemists to induce certain chemical reactions.

Far-ultraviolet lamps produce high-energy, short-wavelength ultraviolet light. Like middle-ultraviolet lamps, they use mercury-vapor tubes; however, far-ultraviolet radiation is easily absorbed by glass, and so the lamp's bulb must be constructed from **quartz**. Far-ultraviolet light has been found to destroy living organisms such as germs and bacteria; for this reason, these lamps are used to sterilize hospital air and equipment. Far-ultraviolet radiation has also been used to kill bacteria in food and milk, giving perishables a much longer shelf life.

A more passive application of ultraviolet light is in **astronomy**. Much of the light emitted by stars, particularly very young stars, is in the ultraviolet range. By observing the output of ultraviolet light, astronomers can determine the **temperature** and composition of stars and interstellar gas, as well as gain insights into the evolution of galaxies. However, most of the ultraviolet light from distant sources is unable to penetrate the Earth's atmosphere; therefore, ultraviolet observations must be made from Earth's orbit by sounding rockets, **space** probes, or astronomical satellites.

See also Electromagnetic spectrum; Solar illumination: Seasonal and diurnal patterns

UNCONFORMITIES

An unconformity is a stratigraphic feature that is formed by broad **erosion** of an **area** causing a significant gap to occur in the stratigraphic record. Generally, development of an unconformity is accompanied by or preceded by uplift of the **rock** units or strata that will be eroded, and/or subsidence or fall of sea level, thus exposing rock units or strata to erosion.

An unconformity can consist of two hypothetical parts: the hiatus and the erosional vacuity. The hiatus is the amount of stratigraphic record removed during erosion and the erosional vacuity is the amount of stratigraphic record that might have been deposited during the time erosion was occurring. The sum of these parts is referred to as the lacuna, or total missing stratigraphic record. An unconformity is commonly referred to as a significant gap in the chronostratigraphic record as well.

Unconformities can be classified according to their scale or scope. For example, a cartographic unconformity is one that can be mapped regionally or seen in a regional cross section. A macrographic unconformity may be seen at outcrop scale where truncation may be evident. A petrographic unconformity is seen under a microscope (usually in a glass-mounted thin section or on the face of a cut slab of rock) and is very small.

Unconformities can also be classified according to their physical appearance. Angular unconformities are those which show truncation of upturned or tilted layers below the unconformity surface. Disconformities are unconformities showing erosional **relief** between otherwise parallel layers of sedimentary strata. A nonconformity is an unconformity developed between igneous or **metamorphic rock** (below) and sedimentary layers (above). Finally, a paraconformity is an enigmatic type of unconformity that appears as a hardly distinguishable plane between two parallel sedimentary rock layers.

Unconformities of large scale (i.e., cartographic unconformities) have been used by some geologists to delineate large groups of sedimentary formations that are bounded by unconformities. These unconformity-bounded units are called synthems, and their origin is related to grand cycles of sea-level change and mountain-building in Earth history. Either regional or inter-regional unconformities bound these large synthems.

Unconformities are recognized using three types of criteria: physical, structural, and paleontologic. Physical criteria include erosional relief between sedimentary rock layers, mineralized zones in rocks, basal conglomerates, iron-stained zones in rocks, zones of truncation and encrustation of **fossils**, small and large-scale solution (karst) features, and ancient soil horizons. Structural criteria include: dikes and faults truncated by erosion, discordance of structural **dip** between layers, and tectonic deformation. Paleontologic criteria include: abrupt change in fossil assemblage, gaps in evolutionary lineage among fossils, missing fossil zones, bone and tooth conglomerates, and reworked or corroded fossils. In study of unconformities, it is preferred that evidence from at least two of the three categories be used to recognize an unconformity and criteria from all three categories, if possible, be used to assess the scope of an unconformity.

Assessment of the scope of an unconformity, that is the amount of geological history or chronostratigraphic record missing at an unconformity, requires careful study. The scope of an unconformity is commonly situational, i.e., related to the type of sediment and the depositional environment of that sediment. For example, erosional removal of 4 in (10 cm) of deep-sea sediment, wherein rates of sediment accumulation are very low (<0.1 cm/1,000 years), would likely result in a significant gap in the chronostratigraphic record. An unconformity formed in this way might be a paraconformity or petrographic unconformity, which could be quite significant in terms of lost record. However, the erosional removal of 4 in (10 cm) of sediment formed in a depositional environment wherein **sedimentation** rates were much higher would not result in a significant gap in the rock record.

Many erosional surfaces that look superficially like unconformities are in reality usually only minor erosional or scour surfaces. These features are not unconformities, but are instead diastems. Diastems do not rise to the level of unconformity because the amount of missing record is not significant. As noted above, the assessment of such significance is situational, and it may not be known immediately after discovery if an erosional surface is an unconformity or a diastem.

The term stratigraphic break is commonly used instead of unconformity or diastem, particularly where the significance of a stratigraphic break in question is not known or is ambiguous. In other words, an unconformity may be thought of as a stratigraphic break that is significant in terms of lost record and a diastem as an insignificant break by the same measure. It is well established that unconformities and diastems both contribute to the overall incompleteness of the stratigraphic record.

See also Bedding; Chronostratigraphy; Depositional environments; Stratigraphy

UNIFORMITARIANISM

The concept of uniformitarianism is commonly oversimplified in geological textbooks as "the present is a guide to interpreting the past" (or words to that effect). This explanation, however, is not correct about the true meaning of uniformitarianism. In order to understand uniformitarianism, one must examine its roots in the Enlightenment era (c. 1750–1850) and how the term has been distorted in meaning since that time.

Geology is a historical science, yet the phenomena and processes studied by geologists operated under non-historical natural systems that are independent of the time in which they operated. It is clear from the insights of one of geology's founding fathers of the Enlightenment era, **James Hutton** (1726–1797), that he understood this fact very well. In *Theory of the Earth* (1795), he stated: "In examining things present, we have data from which to reason with regard to what has been; and, from what has actually been, we have data for concluding with regard to that which is to happen thereafter." With his book, Hutton popularized the notion of "examining things present...with regard to what has been," but gave the concept no specific name. Hutton did not use the term uniformitarianism and used the word 'uniformity' only rarely.

Charles Lyell (1797–1875), one of geology's founding fathers from later in the Enlightenment era, wrote about the subject matter of uniformitarianism (but did not use that specific term) in his widely read text, *Principles of Geology* (1830). Partly in response to strident criticism that his notions about geology did not conform to Biblical edicts about supernatural catastrophic events, Lyell developed a much more radical and extreme view of the subject matter of the "uniformity of nature." Careful reading of what Lyell laid out in his discussion of the "uniformity of nature" shows that he embraced both the concept of Hutton, which can be summarized as a uniformity of known causes or processes throughout time, and his own separate view that there must be a uniformity of process rates. The latter, more radical aspect of Lyell's "uniformity of nature" was intended to be a statement of general principle to counter the catastrophist interpretations of the past set forth by geologists of the day who were more inclined to look to the scriptures for their geological interpretations. In Lyell's view, a strong notion of uniformity of rates precluded divine (i.e., catastrophic) intervention.

In 1837, the name uniformitarianism was coined by William Whewell (1794–1866) as a term meant to convey Hutton's sense of order and regularity in the operation of nature and Lyell's sense that there was a uniformity of rates of geological processes through time. It is Whewell's definition that became the most common definition of uniformitarianism.

Lyell's work was influential, and he succeeded in imbuing generations of geologists with the notion of a dual foundation for "uniformity of nature." This dual foundation encompassed both uniformity of causes and uniformity of intensity. The former view is more commonly called actualism today, and the latter, gradualism. In large part, the presence of Lyell's strongly defended gradualism succeeded in freeing nineteenth century geology from the firm grasp of Biblical preconception and allowed it to develop as a free, legitimate science.

One of the most elegant statements about (what is now called) actualism was made by John Playfair in his book, *Illustrations of the Huttonian Theory* (1802). He said: "Amid all the revolutions of the globe the economy of Nature has been uniform, and her laws are the only thing that have resisted the general movement. The **rivers** and the rocks, the **seas**, and the continents have been changed in all their parts; but the laws which describe those changes, and the rules to which they are subject, have remained invariably the same." Actualism is not unique to geology, as it is really a basic and broad scientific concept of many fields. Even though Playfair mentions laws, it is, of course, nature herself that is constant, not laws, which have been written by people in order to try to predict nature.

The other side of Lyell's "uniformity of nature," i.e., gradualism, has no such elegant prose behind it. It has been referred to in inglorious terms by some of the leading minds of our time as "false and stifling to hypothesis formation," "a blatant lie," and "a superfluous term...best confined to the past history of geology." In other words, gradualism is no longer considered a valid idea.

Because uniformitarianism has this historical component of uniformity of process rates (i.e., gradualism), many writers have advocated its elimination from the geological vocabulary. Others argue that it should be retained, but with careful notation about its historical meaning. Some writers ignore this historical debate and continue to tout the term uniformitarianism as the most basic principle of geology. The range of misguided meanings of this term from some recent geology texts includes definitions that span the gamut from something near the nineteenth century meaning to the assumption that Earth is very old, to the logical method of geologic investigation.

Careful analysis of geological texts and recent scientific articles shows that there are at least 12 basic fallacies about uniformitarianism, which are perpetuated by some writers. These are:

1. Uniformitarianism is unique to geology;
2. Uniformitarianism was first discussed by James Hutton;
3. Uniformitarianism was named by Lyell, who gave us its modern meaning;
4. Uniformitarianism is the same as actualism, and should be renamed actualism;
5. Uniformitarianism holds that only processes that are currently active could have occurred in the geologic past;
6. Uniformitarianism holds that rates and intensities of geologic processes are constant through time;
7. Uniformitarianism holds that only non-catastrophic or gradual processes have operated during geologic time;
8. Uniformitarianism holds that Earth's conditions have changed little over geologic time;
9. Uniformitarianism holds that the earth is very old;
10. Uniformitarianism is a testable hypothesis, theory, or law;
11. Uniformitarianism applies to the past only as far back as present conditions have existed on the earth's surface;
12. Uniformitarianism holds only that the governing laws of nature are constant through **space** and geologic time.

In the historical analysis of uniformitarianism above, we have seen how these 12 common conceptions are false and misleading. Most scientists argue that uniformitarianism should be kept in its proper historical perspective in the future, and that a more specific term like actualism might supplant uniformitarianism in places where the word is meant to convey strictly the modern concept of uniformity of causes.

See also Geologic time; Stratigraphy

UNSATURATED ZONE

The unsaturated zone is that portion of the subsurface in which the intergranular openings of the geologic medium contain both **water** and air. The unsaturated zone, also known as the vadose zone or the zone of aeration, extends downward from the land surface to the top of the underlying **saturated zone**. Water in the pores of this zone is at a pressure that is lower than **atmospheric pressure**. Most of the water that eventually recharges the saturated zone must first pass through the unsaturated zone.

The movement of water in the unsaturated zone is dominated by capillary action. This tendency of a liquid to be drawn into interstices, is the result of cohesion of water molecules and adhesion of those molecules to the solid material forming the void. Smaller voids produce greater capillary forces frequently great enough to resist the downward force of **gravity**.

Water originating as **precipitation** at the land surface infiltrates into the unsaturated zone and forms a film on the surface of the material surrounding the pore. The adhesion of the water molecules nearest the solid material is greatest. As precipitation events occur, the thickness of the film increases with greater availability of infiltrating water, the capillary force is reduced in magnitude, and water molecules on the outer portion of the film may begin to flow under the influence of gravity. It is only through these transient variations in water availability, film thickness, and capillary pressure that water is able to migrate within the unsaturated zone.

Most plants utilize water from the unsaturated zone. Capillary water may be drawn from the pores by the plant's roots until the capillary forces can no longer be exceeded. This is the wilting point of the plant. The remaining capillary water can only be displaced through **evaporation**.

Research into the characteristics and dynamics of flow within the unsaturated zone is very active. A variety of human activities are controlled by, or may impact, the unsaturated zone. These include agriculture, subsurface pipeline and tank emplacement, and **waste disposal**. The thick unsaturated zone beneath Yucca Mountain in southern Nevada is currently slated for placement of the nation's high-level nuclear waste. The extremely thick unsaturated zone at the site would allow placement of the waste approximately 1,000 ft (305 m) above the saturated zone and nearly the same distance below the land surface. The nature of the unsaturated zone and its ability to isolate the waste from human contact is the subject of detailed investigation.

See also Hydrogeology; Porosity and permeability; Water table

URANUS • *see* SOLAR SYSTEM

UREY, HAROLD (1893-1981)

American chemist

In 1934, Harold Urey was awarded the Nobel Prize in chemistry for his discovery of deuterium, an isotope, or species, of hydrogen in which the atoms weigh twice as much as those in ordinary hydrogen. Also known as heavy hydrogen, deuterium became profoundly important to future studies in many scientific fields, including chemistry, **physics**, and medicine. Urey continued his research on isotopes over the next three decades, and during World War II, his experience with deuterium proved invaluable in efforts to separate isotopes of uranium from each other in the development of the first atomic bombs. Later, Urey's research on isotopes also led to a method for determining the earth's atmospheric **temperature** at various periods in past history. Already a scientist of great honor and achievement, Urey's last great period of research brought together his interests and experiences to a study of the **origin of life** on Earth. Urey's experimentation has become especially relevant because of concerns about the possibility of global **climate** change.

Urey hypothesized that the earth's primordial atmosphere consisted of reducing gases such as hydrogen, ammonia, and methane. The energy provided by electrical discharges in the atmosphere, he suggested, was sufficient to initiate chemical reactions among these gases, converting them to the simplest compounds of which living organisms are made, amino acids. In 1953, Urey's graduate student Stanley Lloyd Miller carried out a series of experiments to test this hypothesis. In these experiments, an electrical discharge passed through a **glass** tube containing only reducing gases resulted in the formation of amino acids.

The **Miller-Urey experiment** is a classic experiment in molecular biology and genetics. The experiment established that the conditions that existed in Earth's primitive atmosphere were sufficient to produce amino acids, the subunits of proteins comprising and required by living organisms. In essence, the Miller-Urey experiment fundamentally established that Earth's primitive atmosphere was capable of producing the building blocks of life from inorganic materials.

The Miller-Urey experiment also remains the subject of scientific debate. Scientists continue to explore the nature and composition of Earth's primitive atmosphere and thus, continue to debate the relative closeness of the conditions of the experimental conditions to Earth's primitive atmosphere.

Urey was born in Walkerton, Indiana. His father, Samuel Clayton Urey, was a schoolteacher and lay minister in the Church of the Brethren. His mother was Cora Reinoehl Urey. After graduating from high school, Urey hoped to attend college but lacked the financial resources to do so. Instead, he accepted teaching jobs in country schools, first in Indiana (1911–1912) and then in Montana (1912–1914) before finally entering Montana State University in September of 1914, at the age of 21. Urey was initially interested in a career in biology, and the first original research he ever conducted involved a study of microorganisms in the Missoula River. In 1917, he was awarded his Bachelor of Science degree in zoology by Montana State.

The year Urey graduated also marked the entry of the United States into World War I. Although he had strong pacifist beliefs as a result of his early religious training, Urey acknowledged his obligation to participate in the nation's war effort. As a result, he accepted a job at the Barrett Chemical Company in Philadelphia and worked to develop high explosives. In his Nobel Prize acceptance speech, Urey said that this experience was instrumental in his move from industrial chemistry to academic life.

At the end of the war, Urey returned to Montana State University, where he began teaching chemistry. In 1921, he decided to resume his college education and enrolled in the doctoral program in physical chemistry at the University of California at Berkeley. His faculty advisor at Berkeley was the great physical chemist Gilbert Newton Lewis. Urey received his doctorate in 1923 for research on the calculation of heat capacities and entropies (the degree of randomness in a system) of gases, based on information obtained through the use of a spectroscope. He then left for a year of postdoctoral study at the Institute for Theoretical Physics at the University of Copenhagen where **Niels Bohr**, a Danish physicist, was researching the structure of the **atom**. Urey's interest in Bohr's research had been cultivated while studying with Lewis, who had proposed many early theories on the nature of chemical bonding.

Upon his return to the United States in 1925, Urey accepted an appointment as an associate in chemistry at the Johns Hopkins University in Baltimore, a post he held until 1929. He briefly interrupted his work at Johns Hopkins to marry Frieda Daum in Lawrence, Kansas, on June 12, 1926. Daum was a bacteriologist and daughter of a prominent Lawrence educator. The Ureys later had four children.

In 1929, Urey left Johns Hopkins to become associate professor of chemistry at Columbia University, and in 1930 he published his first book, *Atoms, Molecules, and Quanta,* written with A. E. Ruark. Writing in the *Dictionary of Scientific Biography,* Joseph N. Tatarewicz called this work "the first comprehensive English language textbook on atomic structure and a major bridge between the new quantum physics and the field of chemistry." At this time he also began his search for an isotope of hydrogen. Since Frederick Soddy, an English chemist, discovered isotopes in 1913, scientists had been looking for isotopes of a number of elements. Urey believed that if an isotope of heavy hydrogen existed, one way to separate it from the ordinary hydrogen isotope would be through the vaporization of liquid hydrogen. Urey's subsequent isolation of deuterium made Urey famous in the scientific world, and only three years later he was awarded the Nobel Prize in chemistry for his discovery.

During the latter part of the 1930s, Urey extended his work on isotopes to other elements besides hydrogen. Urey found that the mass differences in isotopes can result in modest differences in their reaction rates.

The practical consequences of this discovery became apparent during World War II. In 1939, word reached the United States about the discovery of **nuclear fission** by the German scientists Otto Hahn and Fritz Strassmann. The military consequences of the Hahn-Strassmann discovery were apparent to many scientists, including Urey. He was one of the first, therefore, to become involved in the U.S. effort to build a nuclear weapon, recognizing the threat posed by such a weapon in the hands of Nazi Germany. However, Urey was deeply concerned about the potential destructiveness of a fission weapon. Actively involved in political topics during the 1930s, Urey was a member of the Committee to Defend America by Aiding the Allies and worked vigorously against the fascist regimes in Germany, Italy, and Spain. He explained the importance of his political activism by saying "no dictator knows enough to tell scientists what to do. Only in democratic nations can science flourish."

Urey worked on the Manhattan Project to build the nation's first atomic bomb. As a leading expert on the separation of isotopes, Urey made critical contributions to the solution of the Manhattan Project's single most difficult problem, the isolation of uranium–235.

At the conclusion of World War II, Urey left Columbia to join the Enrico Fermi Institute of Nuclear Studies at the University of Chicago, where Urey continued to work on new applications of his isotope research. During the late 1940s and early 1950s, he explored the relationship between the isotopes of **oxygen** and past planetary climates. Since isotopes differ in the rate of chemical reactions, Urey said that the amount of each oxygen isotope in an organism is a result of atmospheric temperatures. During periods when the earth was warmer than normal, organisms would take in more of a lighter isotope of oxygen and less of a heavier isotope. During cool periods, the differences among isotopic concentrations would not be as great. Over a period of time, Urey was able to develop a scale, or an "oxygen thermometer," that related the relative concentrations of oxygen isotopes in the shells of sea animals with atmospheric temperatures. Some of those studies continue to be highly relevant in current research on the possibilities of global climate change.

In the early 1950s, Urey became interested in yet another subject: the chemistry of the universe and of the formation of the planets, including Earth. One of his first papers on this topic attempted to provide an estimate of the relative abundance of the elements in the universe. Although these estimates have now been improved, they were remarkably close to the values modern chemists now accept.

In 1958, Urey left the University of Chicago to become Professor at Large at the University of California in San Diego at La Jolla. At La Jolla, his interests shifted from original scientific research to national scientific policy. He became extremely involved in the U.S. **space** program, serving as the first chairman of the Committee on Chemistry of Space and Exploration of the **Moon** and Planets of the National Academy of Science's Space Sciences Board. Even late in life, Urey continued to receive honors and awards from a grateful nation and admiring colleagues.

See also Evolution, evidence of; Evolution; Evolutionary mechanisms; Radioactivity

V

VALLEY GLACIER • *see* GLACIERS

VARVED DEPOSITS • *see* GLACIAL LANDFORMS

VENUS • *see* SOLAR SYSTEM

VINCI, LEONARDO DA (1452-1519)

Italian scientist and artist

A true Renaissance man, Leonardo da Vinci was a painter, inventor, scientist, architect, engineer, mathematician, astronomer, and philosopher. Although centuries after his death he remains known primarily as the artist who painted the "Last Supper" and the "Mona Lisa," Leonardo placed a stronger emphasis on his scientific rather than his artistic endeavors. His investigations into almost every field of known science in his time resulted in plans for everything from airplanes to air conditioning systems. Leonardo was also prolific in the field of mathematics and **physics**, including squaring the circle and calculating the velocity of a falling object.

Born in Vinci, near Florence, Italy, Leonardo was the illegitimate son of Ser Piero da Vinci, a notary, and a peasant woman. Leonardo's father recognized his genius early and ensured that he received a proper education in reading, writing, and arithmetic at his home. Leonardo never attended a university. Rather, at the age of 15, he was sent to Florence, where he became an apprentice painter under Italian sculptor and painter Andrea del Verrocchio (1436–1488). It was during this apprenticeship that Leonardo became absorbed in science, and his interest in technical and mechanical skills was already leading him to sketch various machines. In 1482, Leonardo entered the service of the Duke of Milan as the court painter and advisor on architecture and military issues. According to one report, after studying Euclid, Leonardo became so interested in geometry that he neglected his duties as court painter.

Leonardo's interest in mathematics soon led him to provide several approaches to squaring the circle (constructing a square with the same **area** as a given circle) using mechanical methods. In his notebooks, Leonardo described and drew plans for both a **telescope** and a mechanical calculator. Leonardo also formulated several accurate astronomical theories, including one which stated that Earth rotates around the **Sun**, and another stating the **Moon** shines because of the Sun's reflected light. Leonardo postulated that the shadowing image of the full moon that appears cradled between the horns of the crescent moon each month is illuminated by light reflected from the earth, a conclusion that was reached by German Astronomer **Johannes Kepler** (1571–1630) a century later. Through experimentation, Leonardo concluded that the velocity of a falling object is proportional to the time of its fall, predating Sir Isaac Newton's mathematical theory of force and **gravity**. Leonardo's greatest contribution to science and physics, however, may have been his belief that much of nature could be explained scientifically through a strict adherence to mathematical laws, a fundamental tenet of the philosophy of physics.

Leonardo was a keen observer of the rocks and **fossils** of his native Northern Italy. Among his 4,000 pages of unpublished notes (an unfinished encyclopedic work) are references to **sedimentation** occurring in the Arno riverbed and its floodplain, and observations of rainwater rushing downhill, carrying fossilized **rock** with it. Leonardo reasoned that the fossils he observed embedded in the rocks of mountains were not washed uphill, and therefore, the hillsides had once been the site of the sea floor. He furthered this argument with his identification of fossilized corals and oysters, found more than 100 mi (160 km) inland. In the layers of stratified rocks and fossils, Leonardo grasped the concept of **geologic time**.

The Duke of Milan was defeated by the French Armies in 1499, and the following years were nomadic for Leonardo as he traveled to Mantua and then Venice, where he consulted on architecture and military engineering (Leonardo's notebook included plans for a triple-tier machine gun). Leonardo then returned to Florence briefly and, in 1506, returned to Milan where he worked on various engineering projects. Leonardo spent from 1513 to 1516 in Rome, then moved to France, where King Francis I employed him as a painter, architect, and mechanic. By this time, Leonardo worked little on painting and devoted himself primarily to his scientific studies. Leonardo's thousands of sketches and notes focusing on both practical matters of his day and visions of future scientific accomplishments remain as a testament to Leonardo's prolific genius.

VINE, FRED J. (1939-)

English geophysicist

Frederick J. Vine is best known for his contributions to the theory of **plate tectonics** and has had a distinguished career as a geologist and geophysicist. Born in London, England, Vine was educated at Latymer Upper School, London, and St. John's College, Cambridge University. With his supervisor at Cambridge, **Drummond Matthews** (1931–1997), Vine did crucial work on the process of seafloor spreading.

The German scientist **Alfred Wegener** (1880–1930) proposed in 1915 that there had once been a super-continent, which he named Pangaea, that had slowly moved apart. However, Wegener's **continental drift theory** did not explain how such movement occurred, and was not well received. In the early 1960s, Harry Hess (1906–1969) hypothesized that seafloor spreading was responsible for the motion of the continents. In 1963, Vine and Matthews published a paper in *Nature* titled "Magnetic Anomalies Over Ocean Ridges." In this work, the two scientists proposed an idea which, if confirmed, would provide strong support for the seafloor spreading theory.

It had long been suspected, but not proven, that the earth's **magnetic field** has undergone a number of reversals in polarity in its long history. Vine and Matthews suggested that if ocean ridges were the sites of seafloor creation, and the earth's magnetic field does reverse, then new **lava** emerging would produce **rock** magnetized in the current magnetic field of the earth. Older rock would have an opposing polarity, depending on when it had been created. By 1966, further studies confirmed the theory for all **mid-ocean ridges**. This evidence provided compelling support for the ideas of Wegener, and Hess, and resulted in a revolution in the earth sciences, in which the overlooked theory of continental drift was wholeheartedly adopted.

Vine went on to have a distinguished career. With E. M. Moores he did important research on the **geology** of the Troodos mountains of southern Cyprus. He worked with R. A. Livermore and A. G. Smith on the history of Earth's magnetic field, and together with R. G. Ross he did groundbreaking experimental work on the electrical conductivity of rocks from the lower continental **crust**. From 1967–1970 he was assistant professor of geology and geophysics at Princeton University. Vine returned to the United Kingdom in 1970 and became a Reader in the School of Environmental Sciences at the University of East Anglia, Norwich. He was promoted to professor in 1974, and was Dean from 1977–1980, and again from 1993–1998. Since 1998, Vine has been a Professorial Fellow of the University of East Anglia. He has received a number of honors, including the Chapman Medal of the Royal Astronomical Society (1973), the Charles Chree medal and prize of the Institute of Physics (1977), the Hughes Medal of the Royal Society (1982), and the International Balzan Prize (1981)—all of which were shared with Drummond Matthews. He is also a Fellow of The Royal Society.

See also Mid-ocean ridges and rifts

VOLCANIC ERUPTIONS

A volcanic eruption is the release of molten **rock** and volcanic gases through Earth's **crust** to the surface. Molten rock within the earth, or **magma**, is driven to erupt by buoyancy because it is lighter than the surrounding rock. Dissolved gases within the magma are under great pressure and force magma upwards. The upward migrating magma takes advantage of preexisting zones of weaknesses such as fractures or established volcanic necks until it eventually breaks through the surface.

An eruption may last for a few minutes or many hours and days. An eruption may be only a discharge of steam and gases through a small vent, a relatively mild oozing of **lava** from a **fissure** in a shield **volcano**, or a spectacular explosion that shoots huge columns of gases and debris into the sky. The explosiveness of an eruption depends to a great extent on the composition of the molten rock. Magma high in silica will be more viscous than one low in silica. A high-viscosity magma (such as a **rhyolite**) will tend to trap dissolved gases. The pressure of the gases can build up to the point where they are released in a spontaneous explosive eruption. A less viscous magma (such as a **basalt**) allows volcanic gases to bubble through more easily, preventing great build-ups of pressure, and resulting in calmer outpourings of lava.

The length an eruption is described as an eruptive pulse, eruptive phase, or eruptive episode. An eruptive pulse is a very short event lasting a few seconds to minutes. An eruption that lasts a few hours to days and consists of numerous eruptive pulses is called an eruptive phase. Eruptions that involve repeated pulses and phases over days, months, or years is an eruptive episode.

Volcanic eruptions are described according to explosivity, lava type, and other constituents such as ash, gas, and steam content or the nature of rock fragments produced. Some common eruption types are named for classic types of volcanoes that characterize the eruption. These include Hawaiian, Plinian (Vesuvian), Strombolian, and Vulcanian. Some types of eruptions have more descriptive names, such as effusive and phreatic.

A Hawaiian-type eruption consists of a highly fluid basaltic lava that tends to flow effusively from linear fissures or from a central vent in the production of shield volcanoes. The release is not generally explosive as lava gently flows in streams or through lava tubes. Sometimes the lava accumulates in lava **lakes**. Occasionally, however, more spectacular fountains of lava spurting out from a vent do occur.

A Plinian, or Vesuvian, eruption is a more explosive and potentially destructive event where large amounts of ash, dust, and gas are blown out of a central source at a high velocity. The eruptive cloud often forms a large column extending high into the air above the volcano. Avalanches of hot ash, rock, and gas, called *nuee ardentes*, can travel down the side of the volcano at up to 100 mph (160 kph) are possible, such as the one that covered the Italian city of Pompeii. Rhyolitic to dacitic compositions are common. The name is derived from the historian Pliny, who recorded the eruption of Vesuvius in A.D. 79.

Strombolian eruptions are characterized by discrete episodic explosions or fountains of basaltic lava from a single vent or crater. The eruptive pulses are caused by the release of volcanic gases, and are separated by periods of a few seconds to hours. Lava fragments consisting of partially molten volcanic bombs that become rounded as they fly through the air are commonly produced.

Vulcanian, or hydrovolcanic eruptions are explosive events that release a combination of ash and steam into the air, producing an eruptive column. Fragments of lava are ejected, but owing to a high viscosity or previous cooling, the fragments do not form aerodynamic bombs. The composition of the lava is generally andesitic to dacitic.

An effusive eruption is a general term for any non-explosive release of lava. The lava gently wells up from the ground and overflows, cooling on its way down the slope. Effusive eruptions are common in a Hawaiian type event. When a basaltic effusive eruption occurs on the ocean floor, pillow lavas often form. As the name suggests, pillow basalts are rounded elongate shapes the lava takes due to extrusion under the pressure of the ocean. As pillow lavas continually erupt, they form stacked mounds of pillows. Effusive eruptions may occur with a range of compositions, although they are most common in low viscosity lavas such as basalt.

If cool ground **water** or surface water comes in contact with magma below the surface, a phreatic eruption may occur. This is caused by water that is heated into pressurized steam, creating an explosive eruption driven solely by the steam. Because the eruption is driven by steam, no new rock is formed.

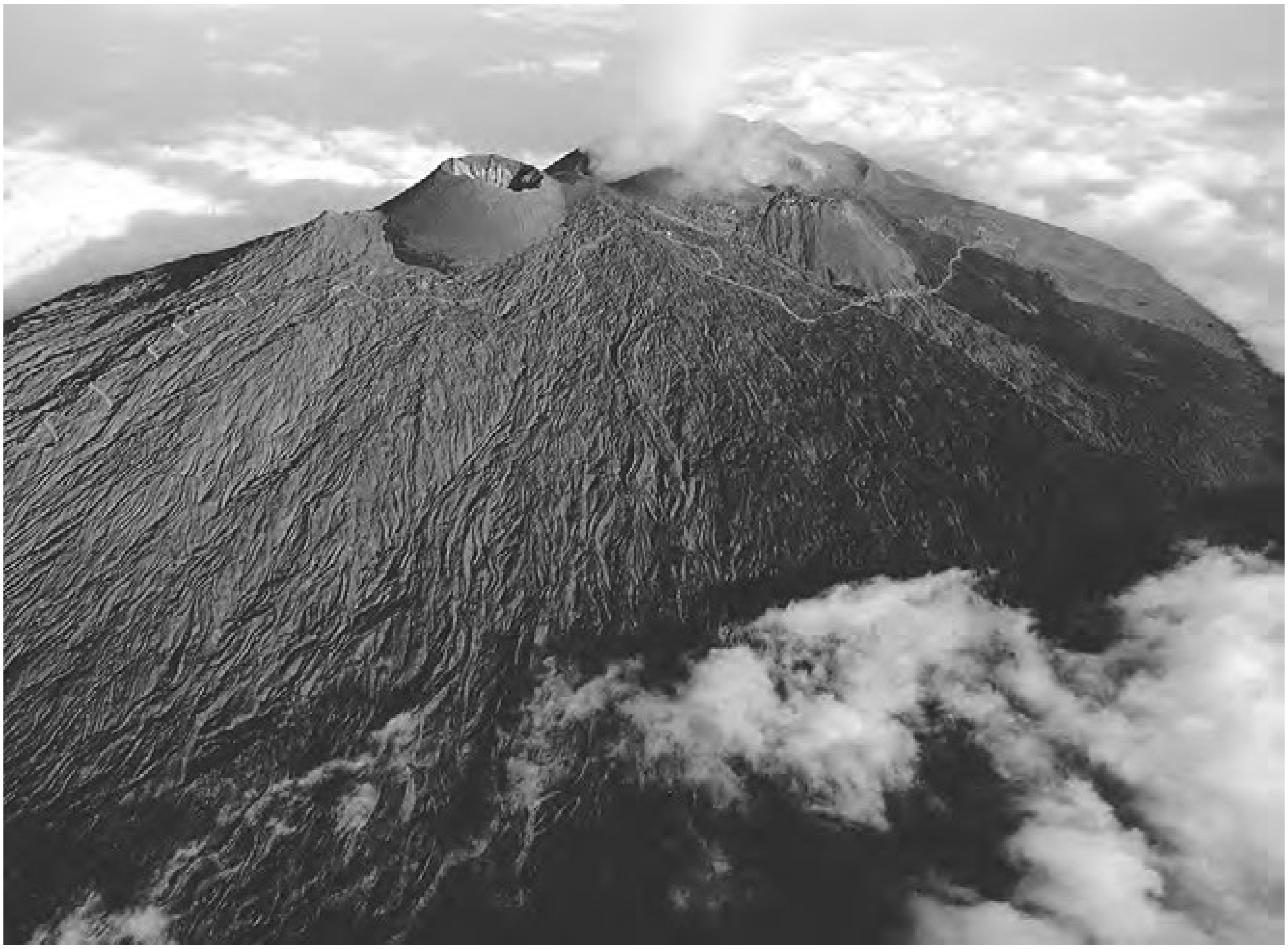
See also Extrusive cooling; Fumerole; Hawaiian island formation; Hotspots; Lahar; Nuee ardent; Pipe, volcanic; Tuff; Volcanic vent

VOLCANIC VENT

Volcanic vents are openings in Earth's **crust** where molten **lava** and volcanic gases escape onto the land surface or into the atmosphere. Most volcanoes have a circular central vent near their summit crater that serves as a conduit for ongoing volcanic construction. Basaltic lavas that cool to form oceanic crust, oceanic plateaus, and continental flood basalts erupt from large, elongate, planar vents called fissures. New oceanic crust is created at axial fissures along the globe-encircling ocean ridge system. Small cracks and ducts in volcanic and hydrothermal provinces serve as vents for escaping lava, gas, and **water** that create smaller-scale volcanic features like gaseous fumaroles, hot **springs**, geysers, and rootless splatter cones called hornitos.

Each of the three main types of volcanoes—cinder cones, shields, and composite volcanoes—forms by eruption of lava, volcanic ash and gases from a central vent. A cinder cone, like Volcan Parícutin in Mexico, begins with an eruption from a vent in the land surface and grows into a steep-sloped, circular mountain as cinders from successive eruptions form a cone around the vent. Shield volcanoes, like the Hawaiian Islands, are composed of low-viscosity basaltic lava that flows easily and rapidly from a central vent. Though sometimes very large, shield volcanoes have a simple structure of stacked, low-angle lava flows around the central vent.

Composite volcanoes, or stratovolcanoes, are very large volcanic edifices composed of alternating layers of volcanic ash, volcanic ejecta and lava flows. Mt. Rainier in Washington, Cotopaxi in Ecuador, Mt. Etna in Sicily, and Mt. Fuji in Japan are stratovolcanos. Extremely large, pyroclastic eruptions of gas-charged, viscous lava issue from a central vent, or group of vents, in the summit crater of a composite **volcano**. However, because the andesitic and rhyolitic lava that composes a stratovolcano is so viscous, the central vent system is often plugged between large eruptions. Lava fills



Mount Etna. ***Photograph by Jonathan Blair. Jonathan Blair/Corbis-Bettmann. Reproduced by permission.***

fissures on the flanks of the mountain creating radial dikes. Gases and fluids also escape from secondary vents, creating fumaroles and hot springs on the slopes of a stratovolcano. When a composite volcano becomes dormant, **erosion** wears away the volcano, leaving the vertical column that cooled in the feeder duct beneath the volcanic vent. Shiprock in New Mexico and Devil's Tower in Wyoming are examples of volcanic necks that formed this way.

See also Mid-ocean ridges and rifts; Volcanic eruptions

VOLCANO

Volcanoes are vents or fissures in Earth's **crust** through which **lava**, gases, and pyroclastic debris are released. More commonly, the term volcano refers to the landform built up from the accumulation of lava and/or pyroclastic debris. Based on the timing of their last eruption, volcanoes are classified as active (having erupted during historic time), dormant (having no recent eruptions, but with the potential to erupt again), or extinct (having no historic eruptions and showing no evidence of future eruptions). There are currently over 500 active volcanoes on Earth's surface, including famous examples such as Mt. Fuji, Mt. St. Helens, and Mauna Loa. Mt. Vesuvius, which last erupted in A.D. 79, is an example of a dormant volcano; Mt. Kilimanjaro is an extinct volcano.

Fueled by Earth's internal processes, volcanoes occur primarily along plate boundaries but also form above hot spots. Eruptive activity may include lava flows, lateral blasts, ash flows, lahars, the release of volcanic gases, or any combination of these. Different types of volcanoes, each with a unique set of characteristics and eruptive styles, include shield volcanoes, composite volcanoes, lava domes, calderas, and cinder cones. Different types of **magma** form under different plate tectonic settings, and the type of magma present determines the type of volcano that will form in a given **area**.

Shield volcanoes, with their gentle slopes and curved profile, are the largest of all volcanoes. They are built up from repeated basaltic flows, often beginning at the ocean floor. Basaltic magma has a relatively low silica content, allowing it to flow readily. As a result, shield volcanoes are characterized by lava flows rather than explosive pyroclastic activity. Shield volcanoes are most commonly formed above hot spots under basaltic oceanic crust. They are also formed in areas where the mid-ocean ridge intersects with land, as in Iceland, or in areas of active **rifting**, like east **Africa**. In these areas, as the magma is rising to the surface, it mixes with only basaltic rocks, allowing it to preserve its **mafic** composition and flow readily. Probably the most famous shield volcanoes, Mauna Loa and Mauna Kea, currently rest above the Hawaiian hotspot. Measured from its base on the ocean floor to its summit, Mauna Kea is 5.6 mi (9 km) tall—slightly taller than Mt. Everest.

Composite volcanoes, also known as stratovolcanoes, have steep sides and a characteristic cone shape. They are built up from alternating layers of lava and pyroclastic debris. Lava associated with composite volcanoes generally has an intermediate composition, and is more resistant to flow than basaltic lava. This results in the mixture of flows and explosions. Composite volcanoes occur above subduction zones, where rising magma mixes with both oceanic and continental crust raising the overall silica content. They are ubiquitous along the subduction zones of the Pacific Rim, and some famous examples include Mt. Fuji in Japan and Mt. Rainier in Washington. Their ability to erupt explosively, as demonstrated by Mt. St. Helens in 1980, makes these some of the most dangerous volcanoes on Earth.

Lava domes are steep-sided, rounded domes, formed because of pressure exerted by rising viscous magma. **Rhyolite**, a **felsic** magma, is usually associated with lava domes. Its felsic composition makes it highly viscous, forcing it to move slowly, building up pressure and deforming the ground surface above. Lava domes are generally associated with composite volcanoes, although they can occur on their own. They are capable of causing deadly eruptions as tremendous amounts of built-up pressure are suddenly released in giant explosions. Eruption of a lava dome was responsible for the death and destruction caused by the 1902 eruption of Mt. Pelée on Martinique.

Calderas are massive depressions created by rare, violent explosions. Also associated with rhyolitic magma, **caldera** eruptions are capable of expelling enormous amounts of ash and debris in a single explosion. Calderas form where **hotspots** occur under continental crust. As magma rises, it mixes with the felsic continental crust, resulting in a high silica content. As is the case with lava domes, the resultant viscous magma cannot flow, and explodes when sufficient pressure has built up. Although there have been none in recent geologic history, about 600,000 years ago a large caldera eruption occurred at what is presently the site of Yellowstone National Park in Wyoming and Montana. The famous hot **springs** and geysers of the area are the legacy of that eruption, and it is believed that the site has the potential to produce another eruption in the future.

Cinder cones are steep-sided, cone-shaped, relatively small volcanoes that are formed by the accumulation of pyroclastic debris. They are not associated with any one particular lava type, and occur in a number of settings. They are commonly found on the flanks or inside the summit craters of larger volcanoes, and form when pyroclastic debris ejected by the main volcano accumulates to form the smaller cone. Perhaps the most famous cinder cone, Parícutin volcano in Mexico, grew suddenly out of a farmer's cornfield and within one month had risen to a height of almost 1,000 ft (305 m). Cinder cones tend to have short life spans; lava flows released by Parícutin eventually covered an extensive area, but within 10 years the volcano became dormant.

See also Convergent plate boundary; Nuee ardent

W

WALTHER, JOHANNES (1860-1937)

German geologist

Johannes Walther (1860–1937) was instrumental in the development of **stratigraphy**. Walther's two-volume work, *Modern Lithogenesis,* published in 1883 and 1884 was a pioneering work in classical sedimentary analysis.

Walther asserted that proper analysis of sedimentary facies could reveal important clues regarding the formation and movement of **rock**. Sedimentary facies are layers within a particular formation that are different in sedimentary history from surrounding layers within the same **area**. Facies may show vertical differentiation, lateral differentiation, or both characteristic differences. The differentiation defining a facies may be either lithological or paleontological.

Walther advanced the ontological method in the analysis of facies stratigraphy. Walther was an avid naturalist, devoted to fieldwork. His data reflected a passion for linking current observation to geologic history.

Near the turn of the century, Walther advanced what is now known as the Walther Facies Rule. Because sedimentary facies show vertical sequence **superposition**, a vertical progression of facies will reflect lateral facies changes. Sedimentary layers or rocks essentially preserve the environment of their deposition. These **depositional environments** change and the old depositional layers shift laterally and may transgress (become superimposed) on surrounding deposits. Regardless, these chronologically transgressive layers will show similar vertical and lateral succession. Walther's rule thus related lateral facies changes to vertical changes (vertical succession). Walther's rule provided a powerful explanation that facies and surrounding deposits change and shift laterally as Earth's surface undergoes change and that lithostratigraphy often reflected layers and formations that can not always be accurately used to date the formations (e.g., where **unconformities** exist). In essence, Walther's rule placed a limit on lithostratigraphic analysis and placed additional reliance upon paleontological analysis of the **fossil record**.

Walther's work was not immediately put to wide use, and Walther suffered the same isolation experienced by many German scientists in an early twentieth century and post World War I environment often hostile to Germany and German scientists. Ultimately Walther's work was appreciated for its wealth of data regarding sedimentary processes and sedimentary facies.

Walther's advancement of facies analysis ultimately proved highly useful in the prediction of formations that might contain **petroleum**, specific minerals, or ores of economic value.

Walther was also an avid and accomplished painter of natural scenes.

See also Dating methods; Marine transgression and marine regression; Petroleum detection; Sedimentary rocks; Sedimentation

WASHINGTON, WARREN M. (1936-)

American meteorologist

Warren M. Washington is an atmospheric scientist whose research focuses on the development of computer models that describe and predict the Earth's **climate**. He is the director of the Climate and Global Dynamics Division of the National Center for Atmospheric Research (NCAR), in Boulder, Colorado. He has advised the U.S. Congress and several U.S. presidents on climate-system modeling, serving on the President's National Advisory Committee on **Oceans** and Atmosphere from 1978 to 1984.

Washington was born in Portland, Oregon. His father, Edwin Washington Jr., had hoped to be a schoolteacher, but in the 1920s, Portland wouldn't hire African-Americans to teach in the public schools. Instead, the elder Washington supported Warren and his four brothers by waiting tables in Pullman cars. His wife, Dorothy Grace (Morton) Washington, became a practical nurse, after the Washington children were grown.

Washington's interest in scientific research developed early and was nurtured by high school teachers who encouraged him to experiment. Refusing once to directly answer his question about why egg yolks were yellow, a **chemistry** teacher inspired Washington to study chicken diets and eventually to learn about the chemistry of sulfur compounds. Despite the boy's aptitude for science, Washington's high school counselor advised him to attend a business school rather than college, but Washington's dream was to be a scientist. He earned his bachelor's degree in **physics** in 1958, from Oregon State University. As an undergraduate, Washington became interested in **meteorology** while working on a project at a **weather** station near the campus. As part of the project, the station used radar equipment to track storms as they came in off the coast. In 1960, he earned his master's degree in meteorology from Oregon State. When he completed his graduate work in 1964 at Pennsylvania State University, he became one of only four African Americans to receive a doctorate in meteorology.

Washington began working for the NCAR in 1963 and has remained affiliated with that institution throughout his career. His research there has attempted to quantify patterns of oceanic and **atmospheric circulation**. He has helped to create complex mathematical models that take into account the effects of surface and air **temperature**, **soil** and atmospheric moisture, sea **ice** volume, various geographical features, and other parameters on past and current climates. His research has contributed to our modern-day understanding of the **greenhouse effect**, in which excess **carbon dioxide** in Earth's atmosphere causes the retention of heat, giving rise to what is known as **global warming**. Washington's research also provided understanding for other mechanisms of global climate change.

Washington was appointed the director of the Climate and Global Dynamics Division at NCAR in 1987. In 1994, he was elected President of the American Meteorological Society. He is a fellow of the American Association for the Advancement of Science and a member of its board of directors, a fellow of the African Scientific Institute, a Distinguished Alumnus of Pennsylvania State University, a fellow of Oregon State University, and Founder and President of the Black Environmental Science Trust, a nonprofit foundation that encourages African-American participation in environmental research and policymaking.

Washington has published over 100 professional articles about atmospheric science. He co-authored, with Claire Parkinson, *An Introduction to Three-Dimensional Climate Modeling* in 1986, and the book has since become a standard reference text for climate modeling. Washington has six children and 10 grandchildren.

WASTE DISPOSAL

Waste management is the handling of discarded materials. Recycling and composting, which transform waste into useful products, are forms of waste management. The management of waste also includes disposal, such as landfilling.

Waste can be almost anything, including food, leaves, newspapers, bottles, construction debris, chemicals from a factory, candy wrappers, disposable diapers, old cars, or radioactive materials. People have always produced waste, but as industry and technology have evolved and the human population has grown, waste management has become increasingly complex.

A primary objective of waste management today is to protect the public and the environment from potentially harmful effects of waste. Some waste materials are normally safe, but can become hazardous if not managed properly. For example, 1 gal (3.75 l) of used motor oil can potentially contaminate one million gal (3,790,000 l) of drinking **water**.

Every individual, business, or organization must make decisions and take some responsibility regarding the management of his or her waste. On a larger scale, government agencies at the local, state, and federal levels enact and enforce regulations governing waste management. These agencies also educate the public about proper waste management. In addition, local government agencies may provide disposal or recycling services, or they may hire or authorize private companies to perform those functions.

Throughout history, there have been four basic methods of managing waste: dumping it, burning it, finding another use for it (reuse and recycling), and not creating the waste in the first place (waste prevention). How those four methods are utilized depends on the wastes being managed. Municipal solid waste is different from industrial, agricultural, or mining waste. Hazardous waste is a category that should be handled separately, although it sometimes is generated with the other types.

The first humans did not worry much about waste management. They simply left their garbage where it dropped. However, as permanent communities developed, people began to dispose of their waste in designated dumping areas. The use of such "open dumps" for garbage is still common in many parts of the world. Open dumps have major disadvantages, however, especially in heavily populated areas. Toxic chemicals can filter down through a dump and contaminate **groundwater**. The liquid that filters through a dump or landfill is called leachate. Dumps may also generate methane, a flammable and explosive gas produced when organic wastes decompose under anaerobic (oxygen-poor) conditions.

The landfill, also known as the "sanitary landfill," was invented in England in the 1920s. At a landfill, the garbage is compacted and covered at the end of every day with several inches of **soil**. Landfilling became common in the United States in the 1940s. By the late 1950s, it was the dominant method for disposing municipal solid waste in the nation.

Early landfills had significant problems with leachate and methane, but those have largely been resolved at facilities built since about the early 1970s. Well-engineered landfills are lined with several feet of **clay** and with thick plastic sheets. Leachate is collected at the bottom, drained through pipes, and processed. Methane gas is also safely piped out of many landfills.

The dumping of waste does not just take place on land. Ocean dumping, in which barges carry garbage out to sea, was once used as a disposal method by some United States coastal cities and is still practiced by some nations. Sewage sludge, or waste material from sewage treatment, was dumped at sea in huge quantities by New York City as recently as 1992, but this is now prohibited in the United States. Also called biosolids, sewage sludge is not generally considered solid waste, but it is sometimes composted with organic municipal solid waste.

Burning has a long history in municipal solid waste management. Some American cities began to burn their garbage in the late nineteenth century in devices called cremators. These were not very efficient, however, and cities went back to dumping and other methods. In the 1930s and 1940s, many cities built new types of more-efficient garbage burners known as incinerators. The early incinerators were rather dirty in terms of their emissions of air pollutants, and beginning in the 1950s they were gradually shut down.

However, in the 1970s, waste burning enjoyed another revival. These newer incinerators, many of which are still in operation, are called “resource recovery” or “waste-to-energy” plants. In addition to burning garbage, they produce heat or **electricity** that can be used in nearby buildings or residences, or sold to a utility. Many local governments became interested in waste-to-energy plants following the energy crisis in 1973. However, since the mid-1980s, it became difficult to find locations to build these facilities, mainly because of public opposition focused on air-quality issues.

Another problem with incineration is that it generates ash, which must be landfilled. Incinerators usually reduce the volume of garbage by 70–90%. The remainder of the incinerated waste comes out as ash that often contains high concentrations of toxic substances.

Municipal solid waste will likely always be landfilled or burned to some extent. In the past 25 years, however, non-disposal methods such as waste prevention and recycling have become more common. Because of public concerns and the high costs of landfilling and burning (especially to build new facilities), local governments want to reduce the amount of waste that must be disposed in these ways.

Municipal solid waste is a relatively small part of the overall waste generated in the United States. More than 95% of the total 4.5 billion tons of solid waste generated in the United States each year is agricultural, mining, or industrial waste.

These wastes do not receive nearly as much attention as municipal solid waste, because most people do not have direct experience with them. Also, agricultural and mining wastes, which make up 88% of the overall total of solid waste, are largely handled at the places they are generated, that is, in the fields or at remote mining sites.

Mining nearly always generates substantial waste, whether the material being mined is **coal**, clay, **sand**, gravel, building stone, or metallic ore. Early mining concentrated on the richest lodes of **minerals**. Because modern methods of mining are more efficient, they can extract the desired minerals from veins that are less rich. However, much more waste is produced in the process.

Many of the plant and animal wastes generated by agriculture remain in the fields or rangelands. These wastes can be beneficial because they return organic matter and nutrients to the soil. However, modern techniques of raising large numbers of animals in small areas generate huge volumes of animal waste, or manure. Waste in such concentrated quantities must be managed carefully, or it can contaminate groundwater or surface water.

Industrial wastes that are not hazardous have traditionally been sent to landfills or incinerators. The rising cost of disposal has prompted many companies to seek alternative methods for handling these wastes, such as waste prevention and recycling. Often a manufacturing plant can reclaim certain waste materials by feeding them back into the production process.

Hazardous wastes are materials considered harmful or potentially harmful to human health or the environment. Wastes may be deemed hazardous because they are poisonous, flammable, or corrosive, or because they react with other substances in a dangerous way.

Industrial operations have produced large quantities of hazardous waste for hundreds of years. Some hazardous wastes, such as mercury and dioxins, may be released as gases or vapors. Many hazardous industrial wastes are in liquid form. One of the greatest risks is that these wastes will contaminate water supplies.

An estimated 60% of all hazardous industrial waste in the United States is disposed using a method called deep-well injection. With this technique, liquid wastes are injected through a well into an impervious **rock** formation that keeps the waste isolated from groundwater and surface water. Other methods of underground burial are also used to dispose hazardous industrial waste and other types of dangerous material.

Pesticides used in farming may contaminate agricultural waste. Because of the enormous volumes of pesticides used in agriculture, the proper handling of unused pesticides is a daunting challenge for waste managers. Certain mining techniques also utilize toxic chemicals. Piles of mining and metal-processing waste, known as waste rock and tailings, may contain hazardous substances. Because of a reaction with the **oxygen** in the air, large amounts of toxic acids may form in waste rock and tailings and leach into surface waters.

Public attitudes also play a pivotal role in decisions about waste management. Virtually every proposed new landfill or waste-to-energy plant is opposed by people who live near the site. Public officials and planners refer to this reaction as NIMBY, which stands for “Not In My BackYard.” If an opposition group becomes vocal or powerful enough, a city or county council is not likely to approve a proposed waste-disposal project. The public also wields considerable influence with businesses. Recycling and waste prevention initiatives enjoy strong public support. About 19% of United States municipal solid waste was recycled or composted in 1994, 10% was incinerated, and 71% was landfilled.

Preventing or reducing waste is typically the least expensive method for managing waste. Waste prevention may also reduce the amount of resources needed to manufacture or package a product. For example, most roll-on deodorants once came in a plastic bottle, which was inside a box. Beginning about 1992, deodorant manufacturers redesigned the bottle so that it would not tip-over easily on store shelves, which eliminated the need for the box as packaging. This is the type of waste prevention called source reduction. It can save businesses money, while also reducing waste.

Waste prevention includes many different practices that result in using fewer materials or products, or using materials that are less toxic. For example, a chain of clothing stores can ship its products to its stores in reusable garment bags, instead of disposable plastic bags. Manufacturers of household batteries can reduce the amount of mercury in their batteries. In an office, employees can copy documents on both sides of a sheet of paper, instead of just one side. A family can use cloth instead of paper napkins.

Composting grass clippings and tree leaves at home, rather than having them picked up for disposal or municipal composting, is another form of waste prevention. A resident can leave grass clippings on the lawn after mowing (this is known as grass-cycling), or can compost leaves and grass in a backyard composting bin, or use them as a mulch in the garden.

When the current recycling boom began in the late 1980s, markets for the recyclables were not sufficiently considered. A result was that some recyclable materials were collected in large quantities but could not be sold, and some ended up going to landfills. Today, the development of recycling markets is a high priority. “Close the loop” is a catchphrase in recycling education; it means that true recycling (i.e., the recycling loop) has not taken place until the new product is purchased and used.

To boost recycling markets, many local and state governments now require that their own agencies purchase and use products made from recycled materials. In a major step forward for recycling, President Bill Clinton issued an executive order in 1993 requiring the federal government to use more recycled products.

Many managers of government recycling programs feel that manufacturers should take more responsibility for the disposal of their products and packaging, rather than letting municipalities bear the brunt of the disposal costs. An innovative and controversial law in Germany requires manufacturers to set up collection and recycling programs for disused packaging of their products.

The high cost of government-created recycling programs is often criticized. Supporters of recycling argue it is still less expensive than landfilling or incineration, when all costs are considered. Another concern about recycling is that the recycling process itself may generate hazardous wastes that must be treated and disposed.

Recycling of construction and demolition (C&D) debris is one of the growth areas for recycling. Although C&D debris is not normally considered a type of municipal solid waste, millions of tons of it have gone to municipal landfills over the years. If this material is separated at the construction or demolition site into separate piles of concrete, wood, and steel, it can usually be recycled.

Composting is considered either a form of recycling, or a close relative. Composting occurs when organic waste—such as yard waste, food waste, and paper—is broken down by microbial processes. The resulting material, known as compost, can be used by landscapers and gardeners to improve the fertility of their soil.

Yard waste, primarily grass clippings and tree leaves, makes up about one-fifth of the weight of municipal solid waste. Some states do not allow this waste to be disposed. These yard-waste bans have resulted in rapid growth for municipal composting programs. In these programs, yard waste is collected by trucks (separately from garbage and recyclables) and taken to a composting plant, where it is chopped up, heaped, and regularly turned until it becomes compost.

Waste from food-processing plants and produce trimmings from grocery stores are composted in some parts of the country. Residential food waste is the next frontier for composting. The city of Halifax, in Canada, collects food waste from households and composts it in large, central facilities.

Biological treatment, a technique for handling hazardous wastes, could be called a high-tech form of composting. Like composting, biological treatment employs microbes to break down wastes through a series of metabolic reactions. Many substances that are toxic, carcinogenic (cancer-causing), or undesirable in the environment for other reasons can be rendered harmless through this method.

Extensive research on biological treatment is in progress. Genetic engineering, a controversial branch of biology dealing with the modification of genetic codes, is closely linked with biological treatment, and could produce significant advances in this field.

Waste management became a particularly expensive proposition during the 1990s, especially for disposal. Consequently, waste managers constantly seek innovations that will improve efficiency and reduce costs. Several new ideas in land-filling involve the reclamation of useful resources from wastes.

For example, instead of just burning or releasing the methane gas that is generated within solid-waste landfills, some operators collect this gas, and then use it to produce power locally or sell it as fuel. At a few landfills, managers have experimented with a bold but relatively untested concept known as landfill mining. This involves digging up an existing landfill to recover recyclable materials, and sometimes to re-bury the garbage more efficiently. Landfill mining has been criticized as costly and impractical, but some operators believe it can save money under certain circumstances.

In the high-tech world of incineration, new designs and concepts are constantly being tried. One waste-to-energy technology for solid waste being introduced to the United States is called fluidized-bed incineration. About 40% of incinerators in Japan use this technology, which is designed to have lower emissions of some air pollutants than conventional incinerators.

A 1994 United States Supreme Court ruling could increase the cost of incineration significantly. The Court ruled that some ash produced by municipal solid-waste incinerators must be treated as a hazardous waste, because of high levels of toxic substances such as **lead** and cadmium. This means that incinerator ash now has to be tested, and part or all of the material may have to go to a hazardous waste landfill rather than a standard landfill.

A much smaller type of incinerator is used at many hospitals to burn medical wastes, such as blood, surgical waste, syringes, and laboratory waste. The safety of these medical waste incinerators has become a major issue in some communities. A study by the Environmental Protection Agency released in 1994 found that medical waste incinerators were leading sources of dioxin emissions into the air. The same study warned that dioxins, which can be formed by the burning of certain chemical compounds, pose a high risk of causing cancer and other health hazards in humans.

The greatest impetus for waste prevention will likely come from the public. More and more citizens will come to understand that pesticides, excessive packaging, and the use of disposable rather than durable items have important environmental costs. Through the growth of the information society, knowledge about these and other environmental issues will increase. This should result in a continuing evolution towards more efficient and environmentally sensitive waste management.

See also Atmospheric pollution; Greenhouse gases and greenhouse effect; Water pollution and biological purification

WASTEWATER TREATMENT

Wastewater often mixes with free-flowing **water** in **rivers**, streams, **oceans**, **lakes**, and other bodies of water. The addition of wastewater can radically alter the chemistry—and the ecological dynamics—of water bodies and hydrologic reservoirs. Wastewater includes the sewage-bearing water that is flushed down toilets as well as the water used to wash dishes and for bathing. Processing plants use water to wash raw material and in other stages of the wastewater treatment production process. The treatment of water that exits households, processing plants, and other institutions is a standard, even mandated, practice in many countries around the world. The purpose of the treatment is to remove compounds and microorganisms that could pollute the water to which the wastewater is discharged. Particularly with respect to microorganisms, the sewage entering a treatment plant contains extremely high numbers of bacteria, viruses, and protozoa that can cause disease if present in drinking water. Wastewater treatment lowers the numbers of such disease-causing microbes to levels that are deemed to be acceptable from a health standpoint. As well, organic matter, solids, and other pollutants that can add to stream load are removed.

Wastewater treatment is usually a multi-stage process. Typically, the first step is known as the preliminary treatment. This step removes or grinds up large material that would otherwise clog up the tanks and equipment further on in the treatment process. Large matter can be retained by screens or ground up by passage through a grinder. Examples of items that are removed at this stage are rags, **sand**, plastic objects, and sticks.

The next step is known as primary treatment. The wastewater is held for a period of time in a tank. Solids in the water settle out while grease, which does not mix with water, floats to the surface. Skimmers can pass along the top and bottom of the holding tank to remove the solids and the grease. The clarified water passes to the next treatment stage, which is known as secondary treatment.

During secondary treatment, the action of microorganisms is often utilized. There are three versions of secondary treatment. One version, which was developed in the mid-nineteenth century, is called the fixed film system. The fixed film in such a system is a film of microorganisms that has developed on a support such as rocks, sand, or plastic. If the film is in the form of a sheet, the wastewater can be overlaid on the fixed film. The domestic septic system represents such a type of fixed film. Alternatively, the sheets can be positioned on a rotating arm, which can slowly sweep the microbial films through the tank of wastewater. The microorganisms are able to extract organic and inorganic material from the wastewater to use as nutrients for growth and reproduction. As the microbial film thickens and matures, the metabolic activity of the film increases. In this way, much of the organic and inorganic load in the wastewater can be removed.

Another version of secondary treatment is called the suspended film. Instead of being fixed on a support, microorganisms are suspended in the wastewater. As the microbes acquire nutrients and grow, they form aggregates that settle out. The settled material is referred to as sludge. The sludge can be scraped up and removed. As well, some of the sludge is added back to the wastewater. This is analogous to inoculating growth media with microorganisms. The microbes in the sludge now have a source of nutrients to support more growth, which further depletes the wastewater of the organic waste. This cycle can be repeated a number of times on the same volume of water.

Sludge can be digested and the methane that has been formed by bacterial fermentation can be collected. Burning of the methane can be used to produce **electricity**. The sludge can also be dried and processed for use as compost.

A third version of secondary treatment utilizes a specially constructed lagoon. Wastewater is added to a lagoon and the sewage is naturally degraded over the course of a few months. The algae and bacteria in the lagoon consume nutrients such as phosphorus and nitrogen. Bacterial activity produces **carbon dioxide**. Algae can utilize this gas, and the resulting algal activity produces **oxygen** that **fuels** bacterial activity. A cycle of microbiological activity is established.

Bacteria and other microorganisms are removed from the wastewater during the last treatment step. Basically, the final treatment involves the addition of disinfectants, such as chlorine compounds or **ozone**, to the water, passage of the water past ultraviolet lamps, or passage of the water under pressure through membranes whose very small pore size impedes the passage of the microbes. In the case of ultraviolet irradiation, the wavelength of the lamplight is lethally disruptive to the genetic material of the microorganisms. In the case of disinfectants, neutralization of the high concentration of the chemical might be necessary prior to discharge of the treated water to a river, stream, lake, or other body of water. For example, chlorinated water can be treated with sulfur dioxide.

Chlorination remains the standard method for the final treatment of wastewater. However, the use of the other systems is becoming more popular. Ozone treatment is popular in **Europe**, and membrane-based or ultraviolet treatments are increasingly used as a supplement to chlorination.

Water is often called the "universal solvent." ***Courtesy of Kelly A. Quin.***

Within the past several decades, the use of sequential treatments that rely on the presence of living material such as plants to treat wastewater by filtration or metabolic use of the pollutants has become more popular. These systems have been popularly dubbed "living machines." Restoration of wastewater to near drinking water quality is possible.

Wastewater treatment is usually subject to local and national standards of operational performance and quality in order to ensure that the treated water is of sufficient quality so as to pose no threat to aquatic life or settlements downstream that draw the water for drinking.

See also Aquifer; Artesian; Drainage basins and drainage patterns; Drainage calculations and engineering; Hydrogeology; Stream capacity and competence

WATER

Water is a chemical compound composed of a single **oxygen atom** bonded to two hydrogen atoms (H2O) that are separated by an angle of 105°. Because of their polar covalent bonds and this asymmetrical bent arrangement, water molecules have a tendency to orient themselves in an electric field, with the positively charged hydrogen toward the negative pole and the negatively charged oxygen toward the positive pole. This tendency results in water having a large dielectric constant, which is responsible for making water an excellent solvent. Water is therefore referred to as the universal solvent. Water can be reused indefinitely as a solvent because it undergoes almost no modification in the process.

Because mineral salts and organic materials can dissolve in water, it is the ideal medium for transporting products of geochemical **weathering** as well as life-sustaining **minerals** and nutrients into and through animal and plant bodies. Brackish and ocean waters may contain large quantities of sodium chloride as well as many other soluble compounds leached from Earth's **crust**.

The concentration of mineral salts in ocean water is about 35,000 parts per million. Water is considered to be potable (drinkable) only if it contains less than 500 parts per million of salts.

Hydrogen bonding, which joins water molecule to water molecule, is responsible for other properties that make water a unique substance. These properties include its large heat capacity, which causes water to act as a moderator of **temperature** fluctuations due to variations in solar illumination, its high surface tension (due to cohesion among water molecules), and its adherence to other substances, such as the walls of a vessel (due to adhesion between water molecules and the molecules of a second substance). The high surface tension makes it possible for surface-gliding insects and broad, flat objects to be supported on the surface of water. Adhesion of water molecules to **soil** particles is the primary mechanism by which water moves through unsaturated soils.

Hydrogen bonding is also responsible for **ice** being less dense than water. If ice did not float, all bodies of water would freeze from the bottom up, becoming solid masses of ice and destroying all life in them. In addition, from season to season, frozen water bodies would remain frozen, resulting in large changes in **climate** and **weather**, such as decreased **precipitation** due to reduced **evaporation**. Ice floats because as the temperature of water is lowered the tendency of water to contract as its molecular motion decreases is overcome by the strength of hydrogen bonding between molecules. At 4°C (39°F), water molecules start to structure themselves directionally along the lines of the hydrogen bonds, at angles of 105° As the temperature drops toward 0°C (32°F), spaces develop between the lines until the open, crystalline form characteristic of ice develops. Its openness produces a density slightly less than that of liquid water, and ice floats on the surface, with approximately nine-tenths submerged.

Water is the only common substance that occurs naturally on earth in three different physical states. The solid state, ice, is characterized by a rigid crystalline structure occurring at or below 0°C (32°F) and occupying a definite volume (found as **glaciers** and ice caps, as snow, hail, and frost, and as **clouds** formed of ice **crystals**). At sea level **atmospheric pressure**, the liquid state exists over a definite temperature range 0°C to 100°C (32 to 212°F), but is not rigid nor does it have a particular shape. Liquid water has a definite volume but assumes the shape of its container. Liquid water covers three-fourths of Earth's surface in the form of swamps, **lakes**, **rivers**, and **oceans** as well as found as rain clouds, dew, and ground water. The gaseous state of water (water vapor) neither occupies a definite volume nor is rigid because it takes on the exact shape and volume of its container. Water vapor (liquid water molecules suspended in the air) occurs in steam, **humidity**, **fog**, and clouds.

During phase changes, one phase does not suddenly replace its predecessor as the temperature changes, but for a time at the **melting** or boiling point, two phases will coexist. As water changes from the gaseous form to the liquid form, it gives off heat at about 540 calories per gram, and as it changes from the liquid form to the solid form, it gives off about 80 calories per gram. The turbulence of thunderstorms is in large part due to the release latent heat of water especially as water condenses into water droplets or into crystals of ice (i.e., hail).

Pressure affects the transition temperature between phases. For example, at pressures below atmospheric, water boils at temperatures under 100°C (212°F), therefore food takes longer to cook at higher elevations.

Water is a major geologic agent of change for modifying Earth's surface through **erosion** by water and ice.

See also Acid rain; Atmospheric chemistry; Chemical bonds and physical properties; Chemical elements; Clouds and cloud types; Condensation; El Nino and La Nina phenomena; Erosion; Evaporation; Freezing and melting; Freshwater; Rate factors in geologic processes

WATER POLLUTION AND BIOLOGICAL PURIFICATION

W**ater** pollution may derive from several sources, including chemical pollutants from industry, **runoff** of chemicals used in agriculture, or debris from geological process, but the greatest source of pollution is organic waste. Although chemical pollutants may become diluted, they can also radically alter the ecosystem to allow the overproduction of certain forms of algae and bacteria that pollute the water with respect to its use by humans.

Once in the water, the growth of microorganisms can be exacerbated by environmental factors such as the water **temperature** and the chemical composition of the water. For example, runoff of fertilizers from suburban properties can infuse watercourses with nitrogen, potassium, and phosphorus. All these are desirable nutrients for bacterial growth.

With specific respect to microorganisms, water pollution refers to the presence in water of microbes that originated from the intestinal tract of humans and other warm-blooded animals. Water pollution can also refer to the presence of compounds that promote the growth of the microbes. The remediation of polluted water—the removal of the potentially harmful microorganisms or the reduction of their numbers to acceptable levels—represents the purification of water.

Microorganisms that reside in the intestinal tract find their way into fresh and marine water when feces contaminate the water. Examples of bacteria that can pollute water in this way are *Escherichia coli*, *Salmonella*, *Shigella*, and *Vibrio cholerae*. Warm-blooded animals other than humans can also contribute protozoan parasites to the water via their feces. The two prominent examples of health relevance to humans are *Cryptosporidium parvum* and *Giardia lamblia*. The latter two species are becoming more common. They are also resistant to chlorine, the most popular purification chemical.

Normally, the intestinal bacteria do not survive long in the inhospitable world of the water. However, if they are ingested while still living, they can cause maladies, ranging from inconvenient intestinal upset to life-threatening infections. An example of the latter is *Escherichia coli O157:H7*. Pollution of the water with this strain can cause severe intestinal damage, life-long damage to organs such as the kidney, and—especially in the young, elderly, and those whose immune systems are compromised—death.

There are several common ways in which microorganisms can pollute water. Runoff from agricultural establish-

Raw sewage being carried by the tide. © *Ecoscene/Corbis. Reproduced by permission.*

ments, particularly where livestock is raised, is one route of contamination. Seasonal runoff can occur, especially in the springtime when rainfall is more pronounced.

Water purification seeks to convert the polluted water into water that is acceptable for drinking, for recreation, or for some other purpose. Techniques such as filtration and exposure to agents or chemicals that will kill the microorganisms in the water are common means of purification. The use of chlorination remains the most widely used purification option. Other approaches are the use of ultraviolet radiation, filters of extremely small pore size (such that even viruses are excluded), and the use of a chemical known as **ozone**. Depending on the situation and the intended use of the finished water, combinations of these techniques can be used.

Purification of drinking water aims to remove as many bacteria as possible, and eliminate those bacteria of intestinal origin. Recreational waters need not be pristine. But bacterial numbers need to be below whatever standard has been deemed permissible for the particular locale.

Another microbiological aspect of water pollution that has become recognized only within the past several years has been the presence in water of agents used to treat bacteria in other environments. For example, a number of disinfectant compounds are routinely employed in the cleaning of household surfaces. In the hospital, the use of antibiotics to kill bacteria is an everyday occurrence. Such materials have been detected in water both before and after municipal **wastewater treatment**. The health effect of these compounds is not known at the present time. However, looking at similar situations, the low concentration of such compounds might propogate the development of resistant bacterial populations.

Natural wetlands also contribute to the purification of water. Wetlands can serve as a depositional sump and provide biological filtering. Normal percolation through **soil** layers also provides a significant source of water purification.

See also Aquifer; Artesian; Drainage basins and drainage patterns; Estuary; Hydrologic cycle

WATER TABLE

In common usage, the term **water** table expresses the surface dividing the unsaturated and saturated **groundwater** zones. More accurately, the water table lies within the **saturated zone** and separates the capillary fringe from the underlying phreatic zone. The phreatic zone is the **area** in which water will freely flow from pores in the geologic material. Within the capillary fringe, however, water is drawn upward from the phreatic zone by capillary action within the pores of the material. Smaller pores produce greater capillary force and cause the water to rise higher, resulting in a thicker capillary fringe. The pores in the capillary fringe are fully saturated, as are those in the phreatic zone. However, the capillary action causes the water in the pores to have a pressure that is lower than **atmospheric pressure**. Water is not able to flow out of these voids.

A more precise definition of the water table is the surface within the saturated zone along which the **hydrostatic pressure** is equal to the atmospheric pressure. Water below this surface has a pressure that is greater than atmospheric pressure while water in voids above is at a pressure that is less than atmospheric pressure.

The shape of the water table is controlled by a number of factors including the water-transmitting characteristics of the geologic medium, and the amount and location of groundwater recharge and discharge. The water table often reflects the surface **topography** of the area with a moderated **relief**. Because mountainous areas have greater **precipitation**, water infiltrating these areas recharges the water table and forms a mound. Groundwater discharges at streams, **lakes**, and wells cause the water table to **dip** toward these points. Between points of recharge and discharge, the water table tilts from areas of high potential (recharge) to areas of low potential (discharge).

The water table moves with changes in the hydrologic system. In periods of **drought** or heavy withdrawals, the water table will fall. During periods of precipitation, the water table moves upward.

A true water table exists only in unconfined aquifers, those where water can percolate directly through the overlying medium to the phreatic zone and the water table is free to move up and down. In confined aquifers, overlying **rock** or sediments with lower **permeability** prevent the water table from moving upward beyond the lower limit of the confining bed. The water in the confined **aquifer** is under pressure and the level to which it would rise, in the absence of the confining bed, is known as the potentiometric surface.

In some instances, a perched water table can form within the **unsaturated zone**, well above the regional water table. This occurs when a layer of low-permeability material, such as a **clay** lens, intercepts percolating water causing it to pool above the layer. A localized phreatic zone forms with the perched water table as its upper limit.

See also Hydrogeology; Porosity and permeability; Springs

WAVE MOTIONS

With regard to **Earth science**, wave motion describes the physical transmission of force or energy potential through a medium of transmission. The transmission disturbs the medium by displacing the medium. For example, **water** waves propagate through displacement (not linear movement) of water molecules; sound waves propagate via displacement of air molecules. Light also propagates via wave—but not in the same manner as water and sound. Light is transmitted via electromagnetic waves, the alternating of disturbances in electrical and magnetic fields.

A single equation is all that is needed to understand wave motion. The first attempt to mathematically describe wave motion was made by Jean Le Rond d'Alembert in 1747. His equation sought to explain the motion of vibrating strings. While d'Alembert's equation was correct, it was overly simplistic. In 1749, the wave equation was improved upon by Leonhard Euler; he began to apply d'Alembert's theories to all wave forms, not just strings. For more than seventy years the equations of Euler and d'Alembert were debated among the European scientific community, most of whom disagreed upon the universality of their mathematics.

In 1822, Jean-Baptiste-Joseph Fourier proved that an equation governing all waves could be derived using an infinite series of sines and cosines. The final equation was provided by John William Strutt (Lord Rayleigh) in 1877, and it is his law of wave motion that is used today. All waves have certain properties in common: they all transmit a change in energy state, whether it be mechanical, electromagnetic, or other; they all require some point of origin and energy source; and almost all move through some sort of medium (with the exception of electromagnetic waves, which travel most efficiently through a vacuum).

There are three physical characteristics that all wave forms have in common—wavelength, frequency, and velocity—and it is this common bond that allows the wave equation to apply to all wave types. In order to understand these physical characteristics, consider one of the most familiar wave forms, the water wave. As a wave passes through water, it forms high and low areas called, respectively, crests and troughs. The wavelength of the water wave is the minimum distance between two identical points, for example, the distance between two consecutive crests or two consecutive troughs. Imagine the water wave striking a barrier, such as a sea wall: the wave will splash against the wall, followed shortly by another, and so on. The amount of time between each splash (the rate at which the wave repeats itself) is the frequency of the wave. Generally, wavelength and frequency are inversely proportional: the higher the frequency, the shorter the wavelength. The final physical characteristic, velocity, is dependent upon the type of wave generated. A mechanical wave, such as our water wave, will move relatively slowly; a sound wave will move much faster (about 1,129 feet or 344 meters per second) while a light wave moves faster still (186,000 miles or 299,200 km per second in a vacuum). It is important to note that while a wave will move through a medium, it does not carry the medium with it. This is hard to picture in our water example, since it appears as if the water does move with the wave. A cork placed in the water moves up and down with the passing of the wave but returns essentially to the same location.

See also Electricity and magnetism; Quantum electrodynamics (QED); Quantum theory and mechanics; Relativity theory; Solar energy

Stratospheric balloon being inflated. ***National Center for Atmospheric Research/University. Corporation for Atmospheric Research/National Science Foundation 221. Reproduced by permission.***

WEATHER BALLOON

The invention of the **weather** balloon inaugurated the age of **remote sensing**, the ability to collect information from unmanned sources. Use of weather balloons is now common in advanced atmospheric research. High altitude weather balloons have also been used by astronomers and cosmologists seeking to take readings of certain particle frequencies or gather light readings free of excessive disturbance from Earth's relatively thick lower atmosphere (**troposphere**).

The first observation balloon was launched immediately before the first manned balloon flight by Frenchmen Jean-François de Rozier and the Marquis d'Aalandes on November 21, 1783, for a pre-flight **wind** reading. Later, French meteorologist Leon Teisserenc de Bort (1855-1913) pioneered the use of weather balloons, handily proving their utility. With balloon-acquired data, he determined the existence of a lower level of the atmosphere, which he termed the troposphere or "sphere of change," where weather takes place. Since the 1930s, when radio tracking systems were invented, balloons have been used as complete floating weather stations, employing such instruments as thermometers, barometers, hygrometers, cameras, and telescopes.

A variety of agencies use weather balloon flights to model the atmosphere and to make more accurate weather predictions. Weather balloons are used widely to collect such atmospheric information as **temperature**, pressure, and **humidity** that can then be plotted on weather maps. Three-dimensional atmospheric modeling is also possible using weather balloons because the instruments they carry are able to provide meteorologists and other atmospheric scientists data collected from a number of altitude points. Since their inception, the elongated bags of helium, a lighter than air element that provides the balloon lift, have been carrying aloft increasingly sophisticated observation devices, taking the science of weather observation literally to the edges of outer **space**.

See also Air masses and fronts; Atmospheric composition and structure; Atmospheric pressure; Atomic mass and weight; History of exploration III (Modern era); History of manned space exploration; International Council of Scientific Unions' World Data Center System; Jet stream; Stratosphere and stratopause; Weather forecasting methods

WEATHER AND CLIMATE

Weather refers to the atmospheric conditions at a certain time or over a certain short period in a given **area**. It is described by a number of meteorological phenomena that include **atmospheric pressure**, **wind** speed and direction, **temperature**, **humidity**, sunshine, cloudiness, and **precipitation**. In contrast, climate refers to long-term, cyclic or seasonal patterns of temperature, precipitation, winds, etc.

Climates are often defined in terms of area, **latitude**, altitude, or other geophysical features. Although there are thousands of microclimate variations, climates can essentially be broken down into four basic types. Hot, moist climates feature high rainfall with often intense and rapid chemical **weathering**. Cold, moist climates still feature chemical weathering but because of the lower temperature, the rates are dramatically reduced from those encountered in hot, moist climates. Cold, dry climates feature the least weathering but mechanical weathering (e.g., **ice** wedging) does produce slow **landscape evolution**. Hot, dry climates often have intense mechanical weathering pressures (e.g., wind, sand-blasting, etc).

The effects of weather also contribute in shaping Earth's surface features. The impact of weather is most pronounced during the occurrence of extreme weather situations, such as prolonged periods of heat, cold, rain, **drought**, and **smog** conditions. In addition, shorter but intense events such as hurricanes, tornadoes, winter **blizzards**, **freezing** rain, and **floods** also produce often-dramatic effects on both the social and geologic landscape. The concern to reduce the impact of weather on public health and property provides an important motivation for the continued efforts by meteorologists and scientists to improve **weather forecasting**.

The study of meteorological phenomena related to both weather and climate changes is an important component in the development of **chaos theory**. Chaos theories are used to study weather-related complex systems in which, out of seemingly random, disordered processes, there arise new processes that are more predictable.

Most of the weather elements on which weather forecasting is based cannot be seen directly, they can only be observed by the effects they create. For the most part, weather variables are measured and recorded by instruments. For example, air subjects everything to considerable pressure. At sea level, the atmosphere exerts approximately 15 lb/in^2 (about 1 kg/cm^2) of pressure. The standard instrument used to measure atmospheric pressure is the mercury barometer. The **physics** for the barometer dates to the classic experiments performed for the first time in 1643 by the Italian scientist **Evangelista Torricelli** (1608–1647). A column of mercury is held in a closed **glass** tube, then inverted and immersed into a mercury dish. The weight of the column is thus balanced by the atmospheric pressure and the length of the column affords a measure of that weight. The mean atmospheric pressure at sea level is 760 mmHg or 1,013 millibars. Pressure as well as air density decrease with increasing altitude and barometric pressure will rise or fall as a function of different weather systems. On weather maps, points of equal pressure are represented by **isobars**.

Wind, by its broadest definition, is any air mass in motion relative to Earth's surface. It is predominantly a horizontal movement. However, localized vertical air motion—updraft or downdraft—also occurs, for example in storms. Wind is described by two quantities: speed and direction. Wind velocity as measured by the anemometer is reported in mi/hr, knots, or km/hr. The wind direction is given by the compass bearing from which the wind blows, for example, a southerly wind blows from the south. The horizontal air movement near Earth's surface is controlled by four forces: the pressure gradient force, the Coriolis force, the centrifugal force, and the frictional forces. The existence of barometric differences in the atmosphere sets up the pressure gradient force that causes air to move from a higher to a lower pressure area. The Coriolis force is the apparent deflection of air mass caused by the **rotation** of Earth. Because of Earth's rotation, there is an apparent deflection of all matter in motion to the right of their path in the northern hemisphere and to the left in the southern hemisphere. For this reason, in the northern hemisphere, high-pressure systems (area of atmospheric divergence) rotate clockwise, low-pressure systems (areas of atmospheric convergence) counterclockwise. These rotational patterns are reversed in the southern hemisphere.

Temperature and humidity are crucial in defining the origins and types of air masses. The thermal properties of an air mass are determined by its latitudinal position on the globe, and its moisture content depends on the underlying surface, be it land or **water**. For example, polar air is cold and dry, whereas tropical air is hot and humid. In essence, the convergence of these two types of air masses is responsible for most global weather activities. The clash of these contrasting air masses leads to the formation of frontal wave depressions moving in an oscillating west-east pattern and steered by the upper-air **jet stream**. Hot, humid tropical air is also the source material that **fuels** the devastating force of hurricanes. Across the network of weather stations, readings of temperature and humidity are taken at regular intervals. Standard equipment in an instrumentation shelter consists of a dry and a wet bulb thermometer, and readings from the two are used to establish the **dew point**. A pair of special thermometers measures the maximum and minimum temperatures occurring during day and nighttime. The hygrometer measures the relative humidity of the air. In fully-automated stations, electronic sensors measure and transmit weather information.

In addition to temperature and humidity, daily weather forecasts inform the public about the heat index during summer and about the **wind chill** index during the winter. These indicators warn the about the possible dangers to human health resulting from exposure to summer heat and winter cold. By combining temperature and humidity, the heat index gives a measure of what temperatures actually feel like. In terms of human health, an increased heat index corresponds to physical activity being more exhausting, resulting in possible heat-related illnesses, cramps, exhaustion, or heatstroke. By contrast, the wind chill factor relates the risk of cold to exposed skin, which may lead to frostbite and hypothermia. The wind chill factor takes into account the effect of wind speed on temperature. For example, a temperature of 20°F (–6.66°C) at a wind-speed of 20 mph (32.18 km/hr) will feel like –10°F (–12.2°C). Humidity is the one factor that not only creates weather activity, but also makes life on Earth possible.

Water exists in one of the following three phases: vapor, liquid, or ice. Water vapor, the invisible gaseous form of water, is always present in the atmosphere; it is defined as the partial pressure of the atmosphere and therefore, like air pressure, it is measured in mmHg. Water vapor supplies the moisture for dew and frost, for **clouds** and **fog**, and for wet and frozen forms of precipitation.

The visible weather elements are, of course, sunshine, clouds, and precipitation. Traditionally, the forecasting of weather was mainly based on the observation of clouds, because their size, shape, and location are the visible indicators of air movement and of changes in water going from vapor to liquid or ice. The first important contribution to the classification of clouds was made in 1802 by the English scientist **Luke Howard**. Based on his observations, clouds were grouped according to three basic shapes: cumulus (heaps), stratus (layers), and cirrus (wispy curls). He also attached the term nimbus to clouds associated with precipitation. From this basic scheme has evolved the modern classification system of clouds by which the lower 10 mi (16 km) of the atmosphere are divided into three layers of clouds characterized by their water phase, i.e., low clouds consisting of water droplets, middle clouds containing a mixture of water droplets and ice **crystals**, and high clouds entirely made up of ice crystals. While some types of clouds are confined to one layer—such as stratus, stratocumulus and smaller type cumuli in the lower layer, altocumulus and altostratus in the middle layer, and cirrus and cirrostratus in the higher layer—other types can occupy two layers, namely, the nimbostratus and the swelling cumulus cloud which can reside in both lower and middle layers, as well as the cirrocumulus found in the middle and higher layers. A third type can expand through all three layers, such as the huge cumulus congestus cloud and of course, the cumulonimbus with its characteristic anvil.

Warm and cold fronts are also distinct in their cloud cover. The first signs of an approaching warm front are the cirrus and cirrostratus clouds, followed by the obscuring altostratus and the thick nimbostratus with continuous precipitation, and occasionally with the formation of patches of stratus clouds. After the passage of the warm front, precipitation ceases and the cloud cover breaks up. The typical cloud of cold fronts is the cumulonimbus and, depending on the instability of the air, nimbostratus. Precipitation will vary from brief showers to heavy, prolonged downpours with **thunder** and **lightning**.

The weather's immediate impact on public health has been demonstrated numerous times by severe events like hurricanes, tornadoes, floods, snow and ice storms, and prolonged periods of extreme heat or cold. In past years, considerable research efforts have been deployed to gain a better understanding of the physics of hurricanes and tornadoes. Better forecasting the path of severe weather systems and broadcasting early warnings has helped decrease the occurrence of weather-related deaths and injuries. Concerns are now increasingly focused on the weather's indirect influence on human health. It has been observed that certain weather situations provide conditions that will, for example, foster the proliferation of insects and consequently the spread of disease. This was the case in 1999 in the eastern regions of the United States, where weeks of drought and heat created the perfect breeding conditions for mosquitoes carrying a type of encephalitis virus. Weather conditions can also heighten the effects of pollution. For example, air pollutants trapped in fog or smog may cause severe respiratory problems. The interrelationship of weather and environmental health issues lends urgency for more **meteorology** research in order to develop the accurate forecasting capabilities required to lower the impact of adverse weather and climate changes on public health.

See also Air masses and fronts; Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Atmospheric pressure; Drought; El Niño and La Nina phenomena; Hydrologic cycle; Isobars; Jet stream; Land and sea breeze; Lightning; Ocean circulation and currents; Seasonal winds; Thunder; Tornado; Tropical cyclone; Weather forecasting methods; Weather radar; Weather satellite; Wind chill; Wind

WEATHER FORECASTING

Weather forecasting is the attempt by meteorologists to predict the state of the atmosphere at some future time and the weather conditions that may be expected. Weather forecasting is the single most important practical reason for the existence of **meteorology** as a science. It is obvious that knowing the future of the weather can be important for individuals and organizations. Accurate weather forecasts can tell a farmer the best time to plant, an airport control tower what information to send to planes that are landing and taking off, and residents of a coastal region when a hurricane might strike.

Humans have been looking for ways to forecast the weather for centuries. The Greek natural philosopher Theophrastus wrote a *Book of Signs*, in about 300 B.C. listing more than 200 ways of knowing when to expect rain, **wind**, fair conditions, and other kinds of weather.

Scientifically-based weather forecasting was not possible until meteorologists were able to collect data about current weather conditions from a relatively widespread system of observing stations and organize that data in a timely fashion. By the 1930s, these conditions had been met. Vilhelm and Jacob Bjerknes developed a weather station network in the 1920s that allowed for the collection of regional weather data. The weather data collected by the network could be transmitted nearly instantaneously by use of the telegraph, invented in the 1830s by Samuel F. B. Morse. The age of scientific forecasting, also referred to as synoptic forecasting, was under way.

In the United States, weather forecasting is the responsibility of the National Weather Service (NWS), a division of the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce. NWS maintains more than 400 field offices and observatories in all 50 states and overseas. The future modernized structure of the NWS will include 116 weather forecast offices (WFO) and 13 river forecast centers, all collocated with WFOs. WFOs also collect data from ships at sea all over the world and from meteorological satellites circling Earth. Each year the Service collects nearly four million pieces of information about atmospheric conditions from these sources.

The information collected by WFOs is used in the weather forecasting work of NWS. The data is processed by nine National Centers for Environmental Prediction (NCEP). Each center has a specific weather-related responsibility: seven of the centers focus on weather prediction—the Aviation Weather Center, the **Climate** Prediction Center, the Hydrometeorological Prediction Center, the Marine Prediction Center, the Space Environment Center, the Storm Prediction Center, and the Tropical Prediction Center—while the other two centers develop and run complex computer models of the atmosphere and provide support to the other centers—the Environmental Prediction Center and NCEP Central Operations. Severe weather systems such as thunderstorms, tornadoes, and hurricanes are monitored at the National Storm Prediction Center in Norman, Oklahoma, and the National Hurricane Center in Miami, Florida. Hurricane watches and warnings are issued by the National Hurricane Center's Tropical Prediction Center in Miami, Florida, (serving the Atlantic, Caribbean, **Gulf of Mexico**, and eastern Pacific Ocean) and by the Forecast Office in Honolulu, Hawaii, (serving the central Pacific). WFOs, other government agencies, and private meteorological services rely on NCEP's information, and many of the weather forecasts in the paper, and on radio and television, originate at NCEP.

Global weather data are collected at more than 1,000 observation points around the world and then sent to central stations maintained by the World Meteorological Organization, a division of the United Nations. Global data also are sent to NWS's NCEPs for analysis and publication.

The less one knows about the way the atmosphere works the simpler weather forecasting appears to be. For example, if **clouds** appear in the sky and a light rain begins to fall, one might predict that rain will continue throughout the day. This type of weather forecast is known as a persistent forecast. A persistent forecast assumes the weather over a particular geographic **area** simply will continue into the future. The validity of persistent forecasting lasts for a few hours, but not much longer because weather conditions result from a complex interaction of many factors that still are not well understood and that may change rapidly.

A somewhat more reliable approach to weather forecasting is known as the steady-state or trend method. This method is based on the knowledge that weather conditions are strongly influenced by the movement of air masses that often can be charted quite accurately. A weather map might show that a cold front is moving across the Great Plains of the United States from west to east with an average speed of 10 mph (16 kph). It might be reasonable to predict that the front would reach a place 100 mi (160 km) to the east in a matter of 10 hours. Since characteristic types of weather often are associated with cold fronts it then might be reasonable to predict the weather at locations east of the front with some degree of confidence.

A similar approach to forecasting is called the analogue method because it uses analogies between existing weather maps and similar maps from the past. For example, suppose a weather map for December 10, 2002, is found to be almost identical with a weather map for January 8, 1993. Because the weather for the earlier date is already known it might be reasonable to predict similar weather patterns for the later date.

Another form of weather forecasting makes use of statistical probability. In some locations on Earth's surface, one can safely predict the weather because a consistent pattern has already been established. In parts of Peru, it rains no more than a few inches per century. A weather forecaster in this region might feel confident that he or she could predict clear skies for tomorrow with a 99.9% chance of being correct.

The complexity of atmospheric conditions is reflected in the fact that none of the forecasting methods outlined above is dependable for more than a few days, at best. This reality does not prevent meteorologists from attempting to make long-term forecasts. These forecasts might predict the weather a few weeks, a few months, or even a year in advance. One of the best known (although not necessarily the most accurate) of long-term forecasts is found in the annual edition of the *Farmer's Almanac*.

The basis for long-range forecasting is a statistical analysis of weather conditions over an area in the past. For example, a forecaster might determine that the average snow fall in December in Grand **Rapids**, Michigan, over the past 30 years had been 15.8 in (40.1 cm). A reasonable way to try estimating next year's snowfall in Grand Rapids would be to assume that it might be close to 15.8 inches (40.1 cm).

Today this kind of statistical data is augmented by studies of global conditions such as winds in the upper atmosphere and ocean temperatures. If a forecaster knows that the **jet stream** over Canada has been diverted southward from its normal flow for a period of months, that change might alter **precipitation** patterns over Grand Rapids over the next few months.

The term "numerical" weather prediction is something of a misnomer because all forms of forecasting make use of numerical data such as **temperature**, **atmospheric pressure**, and **humidity**. More precisely, numerical weather prediction refers to forecasts that are obtained by using complex mathematical calculations carried out with high-speed computers.

Numerical weather prediction is based on mathematical models of the atmosphere. A mathematical model is a system of equations that attempt to describe the properties of the atmosphere and changes that may take place within it. These equations can be written because the gases that comprise the atmosphere obey the same physical and chemical laws that gases on Earth's surface follow. For example, Charles' Law says that when a gas is heated, it tends to expand. This law applies to gases in the atmosphere as it does to gases in a laboratory.

The technical problem that meteorologists face is that atmospheric gases are influenced by many different physical and chemical factors at the same time. A gas that expands according to Charles' Law may also be decomposing because of chemical forces acting on it. How can anyone make use of all the different chemical and physical laws operating in the atmosphere to come up with a forecast of future atmospheric conditions? The answer is mathematically complex. The task is not too much for computers, however. Computers can perform a series of calculations in a few hours that would take a meteorologist his or her whole lifetime to finish.

In numerical weather predicting, meteorologists select a group of equations that describe the conditions of the atmosphere as completely as possible for any one location at any one time. This set of equations can never be complete because even a computer is limited as to the number of calculations it can complete in a reasonable time. Thus, meteorologists pick out the factors they think are most important in influencing the development of atmospheric conditions. These equations are fed into the computer. After a certain period of time, the computer will print out the changes that might be expected if atmospheric gases behave according to the scientific laws to which they are subject. From this printout a meteorologist can make a forecast of the weather in an area in the future.

The accuracy of numerical weather predictions depend primarily on two factors. First, the more data that is available to a computer, the more accurate its results. Second, the faster the speed of the computer, the more calculations it can perform, and the more accurate its report will be. In the period from 1955 (when computers were first used in weather forecasting) to the current time, the percent skill of forecasts has improved from about 30% to more than 60%. The percent skill measure was invented to describe the likelihood that a weather forecast will be more accurate than pure chance.

Forecast accuracy also is difficult to judge because the average person's expectations probably have increased as the percent skill of forecasts also has increased. A hundred years ago, few people would have expected to have much idea as to what the weather would be like 24 hours in the future. Today,

Using mathematical models to automatically analyze data, calculators and computers gave meteorologists the ability to process large amounts of data and to make complex calculations quickly. ***AP/Wide World. Reproduced by permission.***

an accurate next-day forecast often is possible. For periods of less than a day, a forecast covering an area of 100 mi^2 (259 km^2) is likely to be quite dependable.

See also Air masses and fronts; Atmospheric chemistry; Atmospheric circulation; Atmospheric composition and structure; Atmospheric inversion layers; Drought; El Niño and La Nina phenomena; Hydrologic cycle; Isobars; Land and sea breeze; Lightning; Ocean circulation and currents; Thunder; Tornado; Tropical cyclone; Weather forecasting methods; Weather radar; Weather satellite; Wind chill

WEATHER FORECASTING METHODS

Modern **weather forecasting** owes its existence to the invention of many recording **weather** instruments, such as the barometer, hygrometer, **weather balloon**, and radar. Yet, three major technological developments in particular have led weather forecasting from its days of inception to its current status: the development of instant communications beginning in the late 1800s, **remote sensing** devices starting in the early 1900s, and computers in the late 1900s.

Weather recording instruments date from the fifteenth century when **Leonardo da Vinci** invented the hygrometer, an instrument to measure atmospheric **humidity**. About 1643, **Evangelista Torricelli** created the barometer to measure air pressure differences. These instruments were improved upon in the eighteenth century by Frenchman Jean Andre Deluc (1727–1817), and have been refined numerous times since then. Weather information has long been displayed in map form. In 1686, English astronomer **Edmond Halley** (1656–1742) drafted a map to explain regular winds, tradewinds, and monsoons. Over 200 years later, in 1863, French astronomer Edme Hippolyte Marie-Davy (1820–1893) published the first isobar maps, which depicted barometric pressure differences. Weather data allowed scientists to try to forecast weather. The United States Weather Service, established in 1870 under the supervision of Cleveland Abbe, unified communications and forecasting. Telegraph networks made it possible to collect and disseminate weather reports and predictions. By the turn of the twentieth century, the telephone and radio further increased meteorologists' ability to collect and exchange information. Remote sensing, the ability to collect information from unmanned sources, originated with the invention of the weather balloon by Frenchman Leon Teisserenc de Bort (1855–1913). Designed to make simple preflight tests of **wind** patterns, balloons were eventually used as complete floating weather stations with the addition of a radio transmitter to the balloon's instruments. Many scientists added to the pool of meteorological knowledge, including Englishman Ralph Abercromby who, in his 1887 book, *Weather*, depicted a model of a depression that was used for many years.

During World War I, the father-son team of Vilhelm Bjerknes (1862–1951) and Jacob Bjerknes (1897–1975) organized a nationwide weather-observing system in their native Norway. With the available data they formulated the theory of polar fronts: The atmosphere is made up of cold air masses near the poles and warm tropical air masses, and fronts exist where these air masses meet. In the 1940s, Englishman R. C. Sutcliffe and Swede S. Peterssen developed three-dimensional analysis and forecasting methods. American military pilots flying above the Pacific during World War II discovered a strong stream of air rapidly flowing from west to east, which became known as the **jet stream**. The development of radar, rockets, and satellites greatly improved data collection. **Weather radar** first came into use in the United States in 1949 with the efforts of Horace Byers (1906–1998) and R. R. Braham. Conventional weather radar shows **precipitation** location and intensity.

In the 1990s, the more advanced Doppler radar, which can continuously measure wind speed in addition to precipitation location and intensity, came into wide use. Using mathematical models to automatically analyze data, calculators and computers gave meteorologists the ability to process large amounts of data and to make complex calculations quickly. Today the integration of communications, remote sensing, and computer systems makes it possible to predict the weather almost simultaneously. Weather satellites, the first launched in 1960, can now produce sequence photography showing cloud and frontal movements, water-vapor concentrations, and **temperature** changes. With the new radar and computer enhancement, such as coloration, professionals and untrained viewers can better visualize weather information and use it in their daily lives.

See also Air masses and fronts; El Niño and La Nina phenomena; Isobars; Meteorology

WEATHER MAPS • *see* WEATHER FORECASTING METHODS


Doppler radar dishes. ***National Oceanic and Atmospheric Administration (NOAA).***

WEATHER RADAR

Radio Detection And Ranging systems, known as radar, were developed in Britain in the 1930s as a defense against German bombing raids. While their military use flourished during World War II, radar was not used commercially until the 1950s. Today, radar has become commonplace. Flight crews routinely use radar-tracking features to navigate aircraft to their destinations safely. Radar is also commonly used by meteorologists to track **weather** patterns. For most television viewers of the weather forecast, the image of a green, circular radar screen—complete with a sweeping arm of light—is a familiar one. Using a high-intensity microwave transmission, meteorologists can detect and follow large masses of **precipitation**, whether they occur as rain, snow, or **clouds**.

A weather radar **projection** begins with a pulsed microwave beam that travels until it hits an obstacle (for meteorological purposes, a cloud or band of precipitation). It is then reflected back to the source, where it is received by a radar antenna. By measuring the time taken for the signal to reach the obstacle and return, its distance can be easily calculated. With thousands of pulses emitting and returning, a two-dimensional image of the weather formation is displayed on a cathode-ray tube, showing its precise position. A more elaborate version of radar tracking, called Doppler radar, uses a continuous signal rather than a pulsed wave. Doppler radar can determine both the direction and velocity of **wind** patterns, as well as areas of precipitation. Doppler radar measures the shift in frequency caused by a moving particle. If the returning frequency is higher than when transmitted, the particle is moving toward the source; if it is lower, the particle is moving away. However, the system only works when a particle is approaching or receding from the transmitter; Doppler radar cannot detect the velocity of a particle moving perpendicular to the radar signal. For this reason, signals from more than one radar source must be combined to produce an image free of gaps.

Unlike standard radar, a Doppler system can reliably detect the presence of funnel clouds and tornadoes, and is now used quite commonly by weather forecasters, as well as radio and television stations, to monitor thunderstorms for the presence of strong winds and tornadoes. Doppler radar can provide potentially life-saving readings at a relatively small cost increase over standard radar.

See also Air masses and fronts; Weather forecasting methods; Weather satellite

WEATHER SATELLITE

The first attempt to look at Earth's **weather** from **space** occurred early in the space program of the United States. In 1959, Vanguard II was launched with light-sensitive cells able to provide information about Earth's cloud cover. Unfortunately, the **satellite** tumbled in orbit and was unable to return any information. Explorer VI, also launched in 1959, was more successful and transmitted the first photographs of Earth's atmosphere from space.

In 1960, the United States launched the first experimental weather satellite, TIROS 1. The acronym for Television and Infra Red Observation Satellite, TIROS 1 televised over 22,000 photos before it failed six weeks later. It detected potential hurricanes days before they could have been spotted by any other means. It watched the spring breakup of the **ice** in the St. Lawrence River and helped forecast weather for the Antarctic bases. TIROS 1 also used infrared detectors to measure the amount of heat radiated by the earth's surface and the **clouds**. Later versions of TIROS improved upon the original with television cameras that provided direct, real-time readouts of pictures to simple stations around the world. In 1970, ITQS-l was launched with the capability of not only direct-readout, automatic picture transmission but also the ability to store global images for later transmission and processing. Another successful series was called NOAA after the National Oceanic and Atmospheric Administration. Some of these satellites were placed in geostationary orbit (moving at the same speed as Earth) and thus were able to continuously observe one **area**. This helped in the detection of severe storms and tornadoes and provided real-time coverage at an earlier stage of cloud and frontal weather movements. Other TIROS-type satellites, such as NIMBUS (1960s) and NOAA-9 (1980s–1990s), are in polar orbit, where their infrared sensors measure temperatures and **water** vapor over the entire globe.

Several GOES (Geostationary Operational Environmental Satellites) also cover the western and eastern hemispheres. These satellites are able to provide weather reports for places that have not been covered very well in the past: ocean regions, deserts, and polar areas. They also trace hurricanes, typhoons, and tropical storms, in the process save many lives. Their data are used to produce state-of-the-art charts showing sea-surface temperatures, information useful to the shipping and fishing industries. New satellites that probe Earth's atmosphere by day and night in all weather are being developed in many countries. Since the weather satellite is now an established tool of meteorologists all over the world, both developed and developing nations will continue to rely on these crafts.

See also Weather forecasting methods; Weather radar

WEATHER SYSTEMS AND WEATHER FRONTS • *see* AIR MASSES AND FRONTS

WEATHERING AND WEATHERING SERIES

Weathering is the *in situ* (in position) breakdown of rocks by natural forces into sediments or chemical constituents. Weathering may be physical or chemical. Physical weathering is the mechanical disintegration of rocks into finer particles. Chemical weathering is the decomposition of rocks according to the weathering series, a list of **minerals** arranged in order of their relative chemical stability at the earth's surface.

Chemical weathering occurs via a variety of processes such as dissolution, oxidation, hydration, or carbonation. These processes alter minerals at the molecular level either producing, as weathering products, different minerals or non-mineral chemical constituents. Based on their chemical stability, some minerals are more susceptible to the agents and processes of chemical weathering than others. A mineral's stability is determined to a large extent by the conditions under which it formed. Many igneous and metamorphic minerals that equilibrated deep within the earth will be less stable in the very different conditions found at the surface of the earth. These minerals will then be more susceptible to the agents of chemical weathering. This susceptibility follows a general progression called the weathering series. Below is the weathering series with the least stable minerals, the ones that will **weather** first, at the top. It progresses downward toward the more stable and long-lived minerals.

- Olivine—Calcic plagioclase
- Augite
- Hornblende—Alkalic plagioclase
- Biotite
- Potassium feldspar
- Muscovite
- Quartz

The minerals in the weathering series are essentially the same as **Bowen's Reaction Series**, the order in which minerals crystallize from **magma**. It differs, however, in that the weathering series is not a successive progression of weathering products. It does not mean, for example, that **olivine** will break down to form augite, merely that olivine will tend to decompose before augite, if both are present.

Physical weathering is the mechanical fragmentation of **rock** in place. It is differentiated from **erosion,** or mass wastage, which involve the transport of material. Physical weathering is accomplished dominantly by the processes of expansion and cracking due to the unloading of pressure and expansion from crystal growth. Unloading is the release of lithostatic pressure experienced by a body of rock after it has been uplifted to the surface of the earth where the pressure is much less than where it formed deeper within the earth. This

Rain pounding the ground loosens sediments, making surfaces more susceptible to erosion. The resulting runoff from rain carries the loosened sediment away, contributing to the process of disintegration. ***© Richard Hamilton Smith/Corbis. Reproduced by permission.***

pressure change will cause a rock to expand in all directions, dislodging grain boundaries. Often, this type of expansion results in concentric fractures that cause curved portions of the rock to slough off, or exfoliate. Crystal growth includes **ice** formation. **Water** that has permeated a rock, if frozen, will expand and create fractures. A rock can also experience secondary mineral growth, often of evaporite minerals that were transported in solution and infiltrate the rock by capillary action. Other minor agents of physical weathering include vegetation, which can create fractures by root growth, and thermal expansion of rock caused by climate changes.

The rate of rock weathering, whether chemical or physical, is influenced by the type of rock, climate, **topography**, and vegetation. The type of rock includes the **mineralogy**, which determines where in the weathering series the rock lies. It also includes lithologic structures such as number and size of fractures or **bedding** planes, both of which can be sites for focused weathering activity. Climate influences the rate of weathering as well as which type of weathering processes will predominate. For example, frost heaving will not be factor in a very warm climate, and a moist climate will experience more chemical weathering than a dry one. Topography determines how much rock will be exposed to the elements. It also influences the amount of vegetation that may take hold. Vegetation root systems, in addition to physically weathering rock, also produces **carbon dioxide** and humic acid, two chemical weathering agents.

See also Soil and soil horizons

WEGENER, ALFRED (1880-1930)

German meteorologist

Alfred Wegener was primarily a meteorologist who became much more famous for proposing the idea of continental drift. Decades after his death, the theory of continental drift that he had proposed in 1912 became the well-established foundation for the **plate tectonics** revolution in the earth sciences. Wegener heard mostly ridicule of his continental drift idea during his lifetime, but in the 1960s, oceanic data convinced scientists that continents do indeed move. Wegener was an eminent meteorologist in his time, but he was appointed professor late in his professional career, and died during one of his scientific trips to Greenland.

Wegener was born in Berlin, Germany to Richard, a minister and director of an orphanage, and Anna Wegener. From an early age, he hoped to explore Greenland, and he walked, hiked, and skated in order to build up his endurance for such a trip. He studied at the universities in Heidelberg, Innsbruck, and Berlin, receiving a doctorate in **astronomy** from the latter in 1905. Wegener's thesis involved conversion of a thirteenth-century set of astronomical tables into decimal notation; thereafter he abandoned astronomy in favor of **meteorology**. He carried out experiments with kites and balloons, fascinated with the new science of **weather**. In 1906, he and his brother Kurt set a world record in an international balloon contest by flying for 52 hours straight.

That year, Wegener also fulfilled his dream of going to Greenland. Wegener was chosen as official meteorologist for a Danish expedition to northeastern Greenland from 1906 to 1908. It was the first of four trips to Greenland he would take. In 1912, he returned to Greenland with an expedition to study glaciology and climatology; this trip was the longest crossing of the **ice** cap ever made on foot.

In 1908, Wegener accepted a job teaching meteorology at the University of Marburg. His lectures were very popular with students for their clarity and frankness. He admitted disliking mathematical details, yet in 1911 he published a textbook on the thermodynamics of the atmosphere, which included in embryonic form the modern theory on the origins of **precipitation**. The following year Wegener married Else Köppen, the daughter of the "Grand Old Man of Meteorology" in Germany, Wladimir Köppen. During World War I Wegener served as a junior military officer and was wounded twice. After the war he succeeded his father-in-law as director of the meteorological research department of the Marine Observatory near Hamburg. There he conducted experiments to reproduce lunar craters by hurling projectiles at various ground substances, demonstrating that the craters were probably of impact, rather than volcanic, origin. He also continued to analyze the data from Greenland, observe meteorological phenomena, and develop his earlier ideas on the origin of the continents and the **oceans**.

Wegener had first thought of the idea of continental drift in late 1910 while looking at a world map in an atlas. He noticed that the east coast of **South America** matched like a puzzle piece with the west coast of **Africa**, but dismissed the idea of drifting continents as improbable. The next year, however, he came across a list of sources arguing that a land bridge must have connected the two continents at one time, since similar **fossils** from the same time period appeared in both Africa and Brazil. Wegener immediately began to search out fossil evidence to support the idea of drifting continents. Within a few months he presented his hypothesis in two public forums.

Wegener published an extended account of his idea as *Die Entstehung der Kontinente und Ozeane* (The origin of continents and oceans) in 1915. The first edition was only 94 pages long, with no index. The second edition, much expanded and revised, attracted attention in **Europe**. The third edition was translated into English, French, Spanish, Swedish, and Russian in 1924 and was then widely read for the first time. The first English translation correctly referred to the idea of “continental displacement,’’ as Wegener had termed it. The name “continental drift” was coined later.

Wegener’s was the first coherent and logical argument for continental drift that was also supported by concrete evidence. He proposed that a huge supercontinent had once existed, which he named Pangaea, meaning “all land.” He suggested that Pangaea was surrounded by a supersea, Panthalassa, and that 200 million years ago, in the Mesozoic period, Pangaea began to rift into separate continents that moved away from each other. The Americas drifted westward from Europe and Africa, forming the Atlantic Ocean. India moved east from Africa, and **Australia** severed its ties with **Antarctica** and moved towards the equator.

Wegener’s hypothesis departed radically from the accepted view of the earth in his day. Other geologists believed that the earth was still cooling and contracting from a molten mass, and that lighter rocks such as **granite** (termed “sial’’), moved towards the surface, underlain by denser rocks such as **basalt** (“sima”). Mountain ranges, they believed, were produced by the cooling contraction, like wrinkles appearing on a drying fruit. To these scientists, the continents and the ocean basins were initial and set features. It seemed impossible for continents to move through the ocean rocks.

Wegener instead proposed that the lighter sial that made up continents could move horizontally through the oceanic sima; if the continents can rise up vertically, he argued, they must be able to move horizontally as well, as long as sufficient force is provided. Thus the Rocky Mountains and the Andes, on the western edges of the Americas, were formed by the resistance of the sima layer to the continents plowing through them. **Island arcs** like Japan and the West Indies were fragments left behind in the wake of these giant drifting continents.

Wegener’s strongest argument was the similarities of rocks, animals, and plants on both sides of the Atlantic. He pointed to the fossils of several reptiles and flora that were known only in Africa and South America, and to the fact that the distribution of some living animals was hard to explain unless the continents had once been connected. Scientists had previously explained these in terms of a land bridge that had once connected the continents and then sunk into the ocean. Wegener argued that this was impossible; if a bridge was made of sial, it could not simply sink and disappear.

However, Wegener couldn’t find an adequate mechanism to explain continental drift. He suggested two mechanisms, which were later disproved. One was *Pohlflucht*, or “flight from the poles,” to explain why continents seemed to drift towards the equator. *Pohlflucht*, also known as the Eötvös force, came from the fact that the Earth is an oblate spheroid, slightly flattened at the poles and bulging at the equator. Second, Wegener had to explain the westward movement of the Americas; he suggested that some kind of tidal force must be doing the work.

Wegener’s hypothesis was received with ridicule. For decades, other geologists scoffed at the idea of drifting continents. Some scientists supported him, but there was not enough geological evidence to prove beyond a doubt that he was essentially right. Wegener’s first critic was his father-in-law, Köppen, who apparently wanted Wegener to stay in meteorology and not wander into unknown areas like geophysics. At the first lecture in Frankfurt in 1912, some geologists were apparently indignant at the very notion of continental drift. The initial reaction was mixed at best, and hostile at worst. In 1922, when *The Origin of Continents and Oceans* first appeared in English, it was blasted in a critical review and at a scientific meeting. Subsequently, continental drift provoked a huge international debate, with scientists ranging themselves on both sides.

Detractors had plenty of ammunition. It was soon shown that *Pohlflucht* and tidal forces were about one millionth as powerful as they needed to be to move continents. The paleontological evidence was thought to be inconclusive. In 1928, at a meeting of fourteen eminent geologists, seven opposed it, five supported it without reservation, and two supported it with reservations. From then until after World War II, the subject was put on the back burner of scientific debate. In the only major variant on the theory, South African geologist Alex du Toit, a vigorous defender of continental drift, proposed in 1937 that instead of Pangaea there were two **supercontinents**, Laurasia in the northern hemisphere and Gondwanaland in the south.

Many eminent geologists, such as Sir Harold Jeffreys in England and, later, American paleontologist George Gaylord Simpson, were vehement critics of Wegener and his **continental drift theory**. Science historians consider it likely that the prestige of the critics often carried too much weight in the argument over the theory itself. Wegener himself often complained about the narrow-mindedness of geophysicists who could not accept new ideas. In 1926 Wegener was finally given a professorship in meteorology and geophysics at the University of Graz. Four years later he sailed from Copenhagen to Greenland as leader of a major expedition. On November 1 of that year, he and others in the party celebrated his fiftieth birthday at a camp in the center of the Greenland ice cap. Wegener headed for the west coast that day, and apparently died of heart failure. His body was later found about halfway between the two camps.

After World War II, and several decades after Wegener's disappearance, other geologists began to uncover clues that eventually led to the plate tectonics revolution. The development of paleomagnetism in the early 1950s demonstrated that rocks in different continents appeared to have different directions of magnetization, as if continents had drifted apart from each other. In addition, oceanographers began to map the ocean floor to learn about its origin. They learned that the ocean floor was not a fixed glob of sima at all. In 1960, American geologist **Harry Hammond Hess** proposed the theory of seafloor spreading: that the ocean floor is constantly being created at underwater ridges in the middle of the oceans, spreading outward, and being consumed in trenches underneath the continents. By the mid 1960s, new data on magnetic anomalies in the Pacific Ocean revealed that seafloor spreading did indeed occur. Here was the mechanism by which Wegener's continents could drift: The ocean floor was constantly regenerating itself. By the end of the 1960s, continental drift had begun to be accepted by the entire **earth science** community. It had taken half a century, but Wegener's hypothesis became the foundation for a revolution among geologists and a cornerstone for modern views of Earth's history.

See also Convergent plate boundary; Divergent plate boundary

WERNER, ABRAHAM GOTTLOB (1749-1817)

German geologist

One of the founders of **stratigraphy**, Abraham Werner was one of the first to apply the modern **scientific method** to many geological problems, had a powerful and positive influence on his scientists, and was one of the first to attempt a description of the geological history of the world free from religious and mystical explanations.

Werner was born in Wehrau, Silesia (now Germany), although some sources suggest it was the Wehrau in Upper Lusatia, (now Osiecznica, Poland). His father was the inspector of the Duke of Solm's ironworks, and much of Werner's education was designed to prepare him to follow in his father's footsteps. After being taught at home by his father and private tutors he enrolled in the new Bergakademie (Mining Academy) in Freiberg in 1769. While there, he was recruited into the Saxon mining service, but needed a law degree (jurisprudence) in order to advance in his career, and so began studies at the University of Leipzig. Werner found himself distracted by other subjects, especially the history of languages and **mineralogy**.

In 1774, he abandoned his law degree, and left university, but by then he had already published a book, *Von den äusserlichen Kennzeichen der Fossilien*, which was a practical and orderly mineral identification manual. On the strength of his book he gained a teaching position at the Mining Academy in Freiberg. Werner kept the job for the rest of his life, teaching there for over 40 years. He was justly famous for his lectures, and his courses attracted students from all over the Western world.

Werner is remembered most for his water-based theory of the creation of Earth's **crust**. Named Neptunism (after the Roman god of the **oceans**), Werner's ideas, while incorrect, were nonetheless based firmly on the physical evidence of his day. He argued that all older rocks were sedimentary in nature, and had been laid down by an ancient, universal ocean. The different **rock** types and strata were explained by changes in the depth and turbulence of the universal ocean. Werner was one of the first to think of the earth as a whole, and called his new approach "geognosy." Werner's field work, which was mainly in Saxony, convinced him that the opposing view, that ancient rock had a volcanic origin (Vulcanism), was incorrect. In particular, he was sure that **basalt**, a very common rock, was sedimentary, despite strong opposition. To prove his ideas were truly universal many of his students set out across **Europe** looking for supporting evidence. However, many found that outside of Saxony Werner's ideas were not supported at all, and the rival notion of Vulcanism became dominant. It is a tribute to Werner's teaching methods that these students placed such a high degree of importance on what they saw, rather than slavishly following the doctrine of their teacher. Werner tried to tinker with his theory, attempting to make it fit with the new evidence while still retaining the basics, but in doing so it lost much of its simplicity and logic. However, while Neptunism was a dead-end, Werner can be credited with inspiring scientists to think about the natural forces that had created Earth's crust, and with training a generation of inquiring European geologists who went beyond his initial investigations.

He suffered from ill health in his later years, and after 1793 he published very few geological works. Instead he devoted his time to teaching, and a few official duties. Werner was elected to 22 scientific societies in his lifetime, and he was eulogized by followers and opponents alike after his death in Dresden in 1817. He never married, and left most of his estate to the Bergakademie, the school that had been his focus for most of his adult life.

See also Minerals; Sedimentary rocks

WET AIR • *see* HUMIDITY

WILSON, J. TUZO (1908-1993)

Canadian geophysicist

An early proponent of the **continental drift theory**, J. Tuzo Wilson is chiefly remembered for his proposition that **trans-**

form faults were present in the ocean floor, an idea that led to conclusive evidence that the sea floor and the earth's **crust** are constantly moving. Wilson later hypothesized that an ancestral Atlantic Ocean basin had opened and closed during the **Paleozoic Era**, in turn creating the huge land mass known as Pangaea. This theory helps account for the presence of the Appalachian mountains in eastern **North America**, the striking similarity of many **rock** features in Western **Europe** and North America, and parallel cyclical developments on the seven continents.

John Tuzo Wilson was born in Ottawa, Ontario, Canada. His father, John Armitstead Wilson, was an engineer who held a civil service position. His mother, Henrietta Tuzo, was an avid mountain climber who met her husband at the first gathering of Canada's Alpine Club. The Wilsons later shared their love of **geology** and the outdoors with their children, who were brought up to respect the pursuit of knowledge and were educated under the direction of an English governess.

In 1924, Wilson's father obtained a position for him at a forestry camp. Wilson grew so fond of outdoor work that he signed on as an assistant to the legendary mountaineer Noel Odel, who persuaded him to pursue a career in geology. Following his freshman year at the University of Toronto, Wilson switched majors from **physics** to geology. After earning a B.A. in 1930, Wilson received a scholarship to study at Cambridge University under Sir Harold Jeffreys. When Wilson returned to Canada in the early 1930s, he had difficulty finding work, so he continued his education, enrolling in Princeton University, where he earned a Ph.D. in 1936. He made the first recorded ascent of Mount Hague in Montana in 1935, and in 1938 married Isabel Jean Dickson, with whom he eventually had two children.

With the outbreak of World War II in 1939, Wilson joined the Canadian Army. During his seven-year stint, he authored more than 500 technical reports and later claimed that these military papers had helped him develop the lucid prose style that he utilized in a number of scientific studies. By 1946, he had reached the rank of colonel. That same year, after resigning from the army, he succeeded his professor at the University of Toronto. Geophysics had finally become a lucrative field of study in Canada, thanks in large part to the discovery of oil in Alberta, which increased demand for geophysical exploration and led to the development of more advanced instruments and measurement techniques. Wilson investigated a number of geological mysteries, including Canadian **glaciers**, mountain building, and mineral production. He conducted these investigations with a characteristic reverence toward nature: "Everywhere in science modern tools and ideas bring to light the elegant and orderly skeins by which nature builds the glory that we see about us, knit in regular patterns from simple stitches," he wrote in *I.G.Y.: The Year of the New Moons* (1961). "Indeed, we may think of all nature in terms of music, as infinitely ingenious and elaborate variations on a few simple themes."

From 1957 to 1960, Wilson served as president of the International Union of Geodesy and Geophysics. During his tenure he led a series of geologic expeditions to China and Mongolia, the details of which are recorded in his highly praised book, *One Chinese Moon* (1959). In the early 1960s, he became a key figure in what was then the most controversial issue in geology—the continental drift theory.

The origins of the continental drift theory date back hundreds of years. Since the time of the first global maps people have reasoned that at one time the continents might have been a single huge land mass. However, the first formal hypothesis of continental drift was made by German geophysicist **Alfred Wegener** in 1912. The idea was generally overlooked for decades but reemerged prominently in 1960, when geologist Harold Hess theorized that the ocean floors were being continuously created and changed. Hess attributed this activity to two physical structures: **mid-ocean ridges**, where the ocean floor is created, and **ocean trenches**, where the sea floor is destroyed.

Wilson was one of the first scientists to recognize the immense implications of this idea. For the next decade, he was at the very center of this theoretical debate. Using Hess's theory, Wilson postulated the existence of a third category of physical structure on the ocean floor which he called "transform faults," horizontal shears located between ridge sites and trenches. He suggested that transform faults could not exist unless the earth's crust was moving, and that the physical confirmation of these faults might prove the scientific validity of the continental drift theory. In 1967, seismologist Lynn Sykes partially tested Wilson's theory by studying seismic patterns and oceanic focal mechanisms. Wilson brought the idea to the attention of the general public by exhibiting a continental drift model at Montreal's Expo '67. By the late 1960s, the theory had gained wide acceptance and was eventually incorporated into the larger concept of **plate tectonics**, which maintains that the Earth's **lithosphere** is made up of a number of plates that move independently.

Wilson's hypothesis and the publicity it garnered earned him numerous honors, including a Fellowship in the Royal Society (1968), the Penrose Medal of the Geological Society of America (1968), the Walter H. Bucher Medal of the American Geophysical Union (1968), the John J. Carty Medal of the National Academy of Sciences (1975), the Vetlesen Prize of Columbia University (1978), and the Wollaston Medal of the Geological Society of London (1978).

Wilson retired from his professorship at the University of Toronto in 1974. He then assumed the directorship of the Ontario Science Centre and in that capacity helped transform the center from a traditional science museum into an interactive science lab for public use. Of the center's roughly 1,000 exhibits, 400 were designed to be handled by patrons, and during the late 1970s and 1980s, the exploratory museum attracted approximately 1.5 million visitors annually.

Throughout his life Wilson traveled extensively. He lectured at more than 200 colleges and universities. One of his passions was collecting books on the Arctic and Antarctic, both of which he had visited. A mountain range in **Antarctica** was named the Wilson range in his honor. He died in Toronto at the age of 84.

See also Convergent plate boundary; Divergent plate boundary; Sea-floor spreading

WILSON, ROBERT W. (1936-)

American physicist

Robert Woodrow Wilson is best known for the discovery, with co-researcher **Arno Penzias**, of the cosmic background radiation believed to be the remnant of the "big bang" that started the Universe. For their work, Wilson and Penzias were honored with numerous awards, including the 1978 Nobel Prize in physics, which they shared with Pyotr Kapitsa.

Wilson was born in Houston, Texas. He attended Rice University where he received a B.A. in physics in 1957. He then moved on to the California Institute of Technology (Cal Tech) for graduate study and received his Ph.D. in 1962. Wilson's thesis work and post-doctoral research involved making radio surveys (the use of radio waves bounced off of stellar bodies to create visual approximations) of the Milky Way Galaxy. When he heard of the existence of specialized radio equipment at Bell Laboratories, he left Cal Tech and accepted a job at Bell's research facility in Holmdel, New Jersey. This was the very same research facility from which **Karl Jansky**, in the 1930s, almost single-handedly invented the science of radio **astronomy**. Wilson and Penzias, who had preceded Wilson at Bell Labs by about a year, were about to embark on a research odyssey that would culminate in an extremely important discovery almost by accident.

Just as Jansky had done thirty years earlier, Wilson and Penzias were studying the possible causes of static interference that impaired the quality of radio communications. At least, this was what the management at Bell hoped would transpire as the two radio astronomers conducted their research. Wilson and Penzias' long-range plan was to measure radiation in the galactic "halo," a theorized but not well understood cloud of matter and radiation surrounding the Milky Way and other galaxies. Then, they hoped to look for hydrogen gas in clusters of galaxies. Their research instrumentation included a small, sensitive 20-foot microwave "horn" originally designed to receive bounced radio reflections from the Echo communications **satellite**.

Because galactic radio radiation is, by its nature, not very energetic, the central problem in measuring its precise intensity was to eliminate all conceivable sources of heat, or thermal noise, which could obscure an accurate reading of the weak radio signals from **space**. To this end, Penzias had laboriously constructed a "cold load," using frigid liquid helium, which would cool the radio detector down to within only a few degrees above absolute zero. When the equipment was finally ready in the spring of 1964, the radio horn was turned to the sky.

Very early in the research project, it became apparent that the antenna was measuring more radio radiation than Wilson and Penzias had anticipated. The source of the excess radiation could not be determined. A similar problem had surfaced earlier when the twenty-foot horn was used for Echo satellite communications. At that time, researchers added up all the known sources of accounted radio noise, which totaled a heat measurement of 19 degrees Kelvin. It was therefore puzzling to them that the radio receiver was measuring 22 degrees. Wilson and Penzias' results were similar. They had hoped that their carefully modified apparatus would yield more accurate results, but this apparently was not the case. They were measuring a significant amount of excess microwave radiation. The intensity of the signal did not change regardless of where they pointed the receiver. Nor did the radio static appear to be coming from any discrete object in space. The Milky Way Galaxy was not the source either, since the radio signal seemed to be coming from everywhere in the universe at once, not from just a limited zone across the sky. Based on the known sources of radio radiation, the strength of this radiation was far more powerful than expected.

Wilson and Penzias checked for possible explanations for this phenomenon, concluding that atmospheric effects were not to blame. Since the hill upon which their radio horn was perched overlooked New York City, the possibility of interference from man-made sources was considered. After repeated observations, however, Wilson and Penzias were convinced that New York was not to blame. To insure that the signal was not the result of interference from their own electronic apparatus, Wilson and Penzias tracked down and eliminated every conceivable source of noise—including the effects of bird dung, which coated the inside of the radio horn, courtesy of a pair of nesting pigeons. The interior of the radio horn was cleaned out.

The attempts to improve the performance of the radio horn took time. Finally, in 1965, the antenna was re-activated and careful observations were made of the radio flux from the sky. The results revealed that the **telescope** was performing better than ever, but the mysterious excess signal remained. The intensity of the excess radio noise was what would be expected from an object, or source, with a very low temperature—only a few degrees above absolute zero. In this case, as with the previous observation, the static was not coming from a discrete source but was emanating uniformly from every direction in the sky.

While Wilson and Penzias were trying to make sense of what seemed to them to be a failed experiment, Robert Dicke and his colleagues at Princeton University, unaware of the project at Bell Labs, were building a radio receiver of their own designed to look for the very radiation that Wilson and Penzias had unintentionally observed. Whereas Wilson and Penzias had rather modest hopes of making simple surveys of galactic radio flux, Dicke was looking for physical evidence of the creation of the universe. Dicke had been researching the theoretical effects of the big bang, the expanding fireball theorized as the birth of the Universe.

The line of reasoning Dicke followed was that as the universe expanded after the big bang, gases cooled and thinned but were still dense enough to block electromagnetic radiation. All thermal energy released by atoms, including light and heat, was reabsorbed by other atoms in the gas almost instantly. One consequence of this condition was that if someone could have viewed the universe from the "outside" at this point, they would have seen only blackness, since no light could escape the opaque, light-absorbing gas. Eventually, there must have come a time, thousands of years after the big bang, when the average density of the expanding universe was finally low enough to allow heat and light to escape from atoms unimpeded, much as the light and heat generated in the sun's interior eventually escapes through the sun's transparent photosphere. According to the theory that Dicke was exploring, the rapid release of newly freed energy in the thinning, early universe would have taken the form of an incredibly sudden blaze of heat and light, almost like an explosion.

How could this "primeval fireball," as it came to be called, be observed today? If the remnant of this energy flash had survived after several billion years, it would be detected as a kind of "whisper" in a radio telescope. It would have a specific color and **temperature** and would be present in nearly equal intensities in every direction, forming a cosmic background radiation. This radiation would flood every available volume of space. In time, the radiation would appear to cool down to a point near absolute zero, due to the further expansion of the universe, but it would still be detectable even in the present-day universe. It was precisely this radiation that Robert Dicke was preparing to look for with his own radio telescope. It was also this radiation, measuring close to absolute zero (around 3 Kelvin) in uniformity across the sky, that Wilson and Penzias had already discovered.

Wilson and Penzias were not cosmologists, however. They could not explain their observation of the microwave radiation at the 7.3 cm wavelength, and so they contacted Dicke, who they knew was working on this problem. When Dicke heard the details of their findings, he knew that Wilson and Penzias had discovered exactly what he was looking for; the cold, background radiation left over from the big bang. In 1965, Wilson and Penzias published their results in a paper entitled "A Measurement of Excess Antenna Temperature at 4,080 Mc/s." A companion paper written by Dicke, P.J.E. Peebles, P.G. Roll, and D.T. Wilkinson explained the profound cosmological implications of the finding.

The discovery of the cosmic background radiation was like finding the intact skeleton of a dinosaur. The radiation is a "fossil," an ancient relic from a time when the universe was barely 100,000 years old. The discovery of the radiation was to become the second great pillar upon which the **big bang theory** would rest, second only to the 1920s discovery of the expansion of the universe. The fact that the background radiation was predicted in advance of its discovery helped to strengthen the big bang theory, so much so that most competing theories about the birth of the universe, such as steady state, almost immediately fell away after 1965.

As scientists around the world began making their own confirming observations of the cosmic background radiation, it became apparent to those searching past research papers that clues to the existence of the radiation had existed for over 25 years. The most striking example came from 1938, in which optical telescopic observations revealed that interstellar cyanogen gas was being heated, unaccountably, by a 3-degree source. This source was nothing less than the cosmic background radiation. But at the time, no one imagined that the seemingly innocuous source of heat could be the remnants of the big bang fireball. It would not be until Wilson and Penzias's discovery that the cosmic radiation would be identified for what it was.

Wilson and Penzias's discovery was acclaimed by scientists around the world. In 1976, Wilson was named head of the Radio-Physics department of Bell Telephone. For his work on the cosmic background radiation, he also received the Henry Draper Award, in 1977, from the National Academy of Sciences. In 1978, the importance of their achievement in the history of science was fully recognized when Wilson and Penzias shared the Nobel Prize in physics with Kapitsa.

See also Cosmic microwave background radiation

WIND

Wind refers to any flow of air relative to the earth's surface in a roughly horizontal direction. Breezes that blow back and forth from a body of **water** to adjacent land areas—on-shore and off-shore breezes, or land and sea breezes—are examples of local wind. Winds, driven by large pressure systems also exist in great wind belts that comprise the earth's **atmospheric circulation**.

The ultimate cause of Earth's winds is **solar energy**. When sunlight strikes Earth's surface, it heats that surface differently. Newly turned **soil**, for example, absorbs more heat than does snow.

Uneven heating of Earth's surface, in turn, causes differences in air pressure at various locations. On a **weather** map, these pressure differences can be found by locating **isobars**, lines that connect points of equal pressure. The pressure at two points on two different isobars will be different. A pressure gradient is said to exist between these two points. It is this pressure gradient that provides the force that drives air from one point to the other, causing wind to blow from one point to the other. The magnitude of the winds blowing between any two points is determined by the pressure gradient between those two points.

In an ideal situation, one could draw the direction of winds blowing over an **area** simply by looking at the isobars on a weather map. The earth, however, is not an ideal situation. At least two important factors affect the direction in which winds actually blow: the **Coriolis effect** and friction. The Coriolis effect is an apparent force that appears to be operating on any moving object situated on a rotating body, such as a stream of air traveling on the surface of the rotating planet. The Coriolis effect deflects winds from the straightforward direction across isobars. In the Northern Hemisphere, the Coriolis effect tends to deflect winds right of path and in the Southern Hemisphere, it tends to drive winds left of path.

For example, wind in the Northern Hemisphere initially begins to move from west to east as a result of pressure gradient forces. The Coriolis effect results in a deflection of the wind right of path. This results in air moving out of a high-pressure system (an area of divergence) to spin clockwise. Conversely, air moving into a low pressure area (an area of convergence) also deflected right of path, is spun counter-clockwise.

The actual path followed by the wind is a compromise between the pressure gradient force and the Coriolis force. Since each of these forces can range widely in value, the precise movement of wind in any one case is also variable. At some point, the two forces driving the wind are likely to come into balance. At that point, the wind begins to move in a straight line that is perpendicular to the direction of the two forces. Such a wind is known as a geostrophic wind.

The Coriolis effect is most pronounced on winds farther from the surface of the earth. At distances of more than a half a mile or so above the ground pressure gradient and Coriolis forces are the only factors affecting the movement of winds. Thus, air movements eventually reach an equilibrium point between pressure gradient forces and the Coriolis force, and geostrophic winds blow parallel to the isobars on a weather map.

Such is not the case near ground level, however. An additional factor affecting air movements near the Earth's surface is friction. As winds pass over the earth's surface, they encounter surface irregularities and slow down. The decrease in wind speed means that the Coriolis effect acting on the winds also decreases. Since the pressure gradient force remains constant, the wind direction is driven more strongly toward the lower air pressure. Instead of developing into geostrophic winds, as is the case in the upper atmosphere, the winds tend to curve inward towards the center of a low pressure area or to spiral outward away from the center of a high pressure area.

Friction effects vary significantly with the nature of the terrain over which the wind is blowing. On very hilly land, winds may be deflected by 30 degrees or more, while on flat lands, the effects may be nearly negligible.

In many locations, wind patterns exist that are not easily explained by the general principles outlined above. In most cases, unusual topographic or geographic features are responsible for such winds, known as local winds. **Land and sea breezes** are typical of such winds. Because water heats up and cools down more slowly than does dry land, the air along a shoreline is alternately warmer over the water and cooler over the land, and vice versa. These differences account for the fact that winds tend to blow offshore during the evening and onshore during the day.

The presence of mountains and valleys also produces specialized types of local winds. Annual changes in weather patterns produce **seasonal winds** such as the dry Santa Ana winds in Southern California.

See also Air masses and fronts; Atmospheric composition and structure; Atmospheric inversion layers; Jet stream; Weather forecasting methods; Wind chill; Wind shear

WIND BELTS • *see* ATMOSPHERIC CIRCULATION

WIND CHILL

Wind chill is the **temperature** sensed by humans as a result of air blowing over exposed skin. The temperature that humans actually feel, called the *sensible temperature*, can be quite different from the temperature measured in the same location with a thermometer. The reason for such differences is that the human body constantly gives off and absorbs heat in a variety of ways. For example, when a person perspires, **evaporation** of moisture from the skin removes heat from the body, and one feels cooler than the true temperature would indicate.

In still air, skin is normally covered with a thin layer of warm air that insulates the body and produces a sensible temperature somewhat higher than the air around it. When the wind begins to blow, that insulating layer is swept away, and body heat is lost to the surrounding atmosphere. An individual begins to feel colder than would be expected from a thermometer reading at the same location.

The faster the wind blows, the more rapidly heat is lost and the colder the temperature appears to be.

Wind chill charts or conversion tables relate the relationship among actual temperature, wind speed, and wind chill factor, to the temperature felt by a person at the given wind speed. According to standard conversion formulae, a wind speed of 4 mi/h (6 km/h) or less results in no observable change in temperature sensed. At a wind speed of 17 mi/h (30 km/h) and a temperature of 32°F (0°C), however, the perceived temperature is 7°F (-14°C).

Wind chill relationships are not linear. The colder the temperature, the more strongly the wind chill factor is felt. At a wind speed of 31 mi/h (50 km/h), for example, the perceived temperature at 32°F (0°C) is 7°F (-14°C), but at -40°F (-40°C), the perceived temperature is -112°F (-80°C).

See also Antarctica; Atmospheric lapse rate; Aviation physiology; Beaufort wind scale; Humidity; Space physiology

WIND SHEAR

Wind shear is a phenomenon describing highly localized variability in wind speed and/or wind direction. Because wind shear can affect the angle of attack on an airfoil (e.g., the wing, or control surfaces of an airplane) wind shear can cause a loss of lift or control. Dangerous to aviation, wind shear is particularly hazardous when encountered during take-off or landing.

Wind shear is the difference in speed or direction between two layers of air in the atmosphere. Wind shear may occur in either a vertical or horizontal orientation. An example of the former situation is the case in which one layer of air in the atmosphere is traveling from the west at a speed of 31 mph (50 km per hour) while a second layer above it is traveling in the same direction at a speed of 6.2 mph (10 km per hour). The friction that occurs at the boundary of these two air currents is a manifestation of wind shear.

An example of horizontal wind shear occurs in the **jet stream** where one section of air moves more rapidly than other sections on either side of it. In this case, the wind shear line lies at the same altitude as various currents in the jet stream, but at different horizontal distances from the jet stream's center.

Wind shear is a crucial factor in the development of other atmospheric phenomena. For example, as the difference between adjacent wind currents increases, the wind shear also increases. At some point, the boundary between currents may break apart and form eddies that can develop into clear air turbulence or, in more drastic circumstances, tornadoes and other violent storms.

Wind shear has been implicated in a number of disasters resulting in property damage and/or loss of human life. The phenomenon is known as a microburst, a strong localization down draft (down burst) which, when it when reaches the ground, continues as an expanding outflow. For example, it is associated with the movement of two streams of air at high rates of speed in opposite directions. An airplane that attempts to fly through a microburst passes through the wind shear at the boundary of these two air streams. The plane feels, in rapid succession, an additional lift from headwinds and then a sudden loss of lift from tailwinds. In such a case, a pilot may not be able to maintain control of the aircraft in time to prevent a crash.

See also Aerodynamics; Bernoulli's principle; Meteorology; Weather radar; Weather satellite

WOMEN IN THE HISTORY OF GEOSCIENCE • *see* HISTORY OF GEOSCIENCE: WOMEN IN THE HISTORY OF GEOSCIENCE

"WOW!" SIGNAL

Since radio astronomers first tuned into the skies, scientists have listened for an elusive radio signal that would confirm the existence of extraterrestrial life. One of the major efforts in the last quarter of the twentieth century was a project termed the Search for Extraterrestrial Intelligence (**SETI**). Over the years the SETI project evolved into a variety of programs utilizing research resources at a number of different facilities. A number of other programs have embraced at least part of the SETI concept and goals. As of May, 2002, only a fraction of the potential sources of radio signals have been thoroughly observed, and no signal definitively identified as extraterrestrial in origin.

Regardless, there have been a number of interesting possibilities. On August 15, 1977, astronomer Jerry Ehman was going through the computer printouts of an earlier SETI-like project run by Ohio State University (dubbed, "Big Ear"), when he discovered the reception of what remained throughout the twentieth century as the best candidate for a signal that might be classified as a sign of extraterrestrial intelligence. Excited, Ehman scribbled, "WOW!" on the printout and forever after the signal became known as the "WOW!" signal.

Despite repeated attempts to reacquire the signal, the fact that the signal was never again recorded makes many astronomers, including Ehman, skeptical about the origins of the "WOW!" signal. If it were an intentional signal, astronomers argue, the sending civilization would have repeated it—or something like it—many times. A number of SETI experts now assert the "WOW!" signal was, perhaps, a mere reflection of a signal from Earth off an orbiting **satellite**.

See also Astronomy; Cosmology; Electromagnetic spectrum

X

XENOLITH

A xenolith is a **rock** fragment embedded in, and distinct in texture and composition from, a surrounding mass of igneous rock. Xenoliths form when rising **magma** forces its way through channels and cracks, tearing off fragments of their walls and incorporating them into rising magma. These inclusions are termed xenoliths if they did not form from the magma itself, autoliths, or cognate xenoliths, if they were first solidified along the channel walls from the rising magma and re-incorporated later. Single large **crystals** included in igneous rock by the same means as xenoliths are xenocrysts. Xenoliths, which are named from the Greek *xeno* (foreign) and *lith* (rock), typically range from sand-grain size to football size.

When first captured by magma, a xenolith both cools and is heated by the liquid rock around it. How altered it is by heating depends on its size and original **temperature**, on the temperature of its magma bath, and on the proximity of other sources of heating or cooling. If a xenolith is rapidly cooled after capture, its **chemistry** and mineral structure will change little; if it is partly melted before being finally cooled it will undergo some degree of metamorphosis; and if it is thoroughly melted it will blend with the surrounding magma to produce a hybrid or contaminated igneous rock.

Xenoliths may be captured by magma near the surface or deep in the mantle. If mantle-derived xenoliths are carried to the surface rapidly enough to avoid significant metamorphosis they convey valuable data from the depths. For example, some mantle-derived xenoliths consist of a combination of the **minerals olivine**, pyroxene, and garnet. Laboratory **melting** experiments show that the **aluminum** and magnesium content of a pyroxene crystallized in the presence of olivine and garnet depends uniquely on both pressure and temperature. Chemical analysis of an unmetamorphosed mantle-derived xenolith thus reveals the pressure (dependent on depth) and temperature at which it crystallized, giving a temperature reading for a specific depth. Xenoliths can originate hundreds of kilometers underground, far below the reach of the deepest mining or drilling operations, so this data is otherwise unobtainable. Pristine xenoliths also reveal rock textures and compositions deep in the mantle.

See also Country rock; Crater, volcanic; Dike; Hotspots; Magma chamber; Metamorphic rock; Metamorphism; Sill; Volcanic eruptions; Volcanic vent

Y

YEAR, LENGTH OF

Astronomers define a planet's sidereal year as the time the planet requires to make a complete orbit around the **Sun**. A definition more relevant to humans is the time required for the **seasons** to complete one cycle, that is, the time between successive spring equinoxes. This equinoctial year is shorter than the sidereal year because Earth rotates on its axis as it orbits the Sun and the **polar axis** (rotational axis) wobbles like a spinning top (precession), with each wobble taking about 28,000 years. The resulting difference between the equinoctial and sidereal year is small: the equinoctial year is approximately 365 days, 5 hours, 48 minutes, and 46 seconds long, the sidereal year about 20 minutes longer.

The path of Earth around the Sun, like that of every other planet, is an ellipse. However, it is very nearly circular. If one makes the simplifying assumptions that Earth's orbit is circular and that the Sun is stationary, then it is true to say that the length of the sidereal year depends on the distance from Earth to the Sun. Earth's mass, surprisingly, is irrelevant. For example, a planet with twice (or half) Earth's mass, orbiting at the same distance from the Sun as Earth, would have a year of the same length.

However, these are only approximately values. The Sun is not stationary; Earth and Sun are both orbiting around their common center of **gravity**. An Earth year might, therefore, be more accurately described as the time it takes both Earth and Sun to make one complete orbit around their common center of gravity. Even this improved picture ignores the presence of all the other matter in the **solar system** (and the Universe), not to mention relativistic effects. However, because the center of mass is much closer to the Sun—in fact, inside the Sun—astronomers usually assume the Sun to be stationary with regard to Earth's orbit, and for many purposes assume Earth's orbit to be circular.

The lengths of the year, month, and day are not strictly constant. Solar tidal friction is slowly increasing the length of the year by moving Earth away from the Sun; lunar tidal friction is lengthening the month and the day by moving the **Moon** away from Earth and causing the earth to rotate more slowly. The lengthening of the earth's year is negligibly slow, about one billionth of a year every billion years, but the lengthening of Earth's day is much faster: about two seconds every 10,000 years. At the beginning of the **Cambrian Period**, for example, approximately 600 million years ago, there were over 420 days in each year, each only 21 hours long.

See also Astronomy; Tides

YUCCA MOUNTAIN PROPOSED NUCLEAR WASTE REPOSITORY • *see* RADIOACTIVE WASTE STORAGE (GEOLOGICAL CONSIDERATIONS)

Z

ZEOLITE

The zeolites are a group of more than 35 soft, white **minerals** comprised mostly of **aluminum**, **silicon**, and **oxygen** and having a crystal structure featuring spacious pores or rings. Zeolites often form as **crystals** in small cavities in basaltic rocks or as volcanic tuffs altered by **water**. They are also synthesized industrially.

The pores of a natural zeolite crystal are filled with water that can be driven off by heating. The result is a honeycomb-like structure penetrated by openings on the order of a few atoms in width (2–8 angstroms). This structure can act as a hyperfine filter or molecular sieve. For example, nitrogen binds to some zeolites, so forcing ordinary air (which consists mostly of nitrogen) through such crystals yields an output of up to 95% oxygen. Equally useful is the ability of zeolites to capture large positively-charged ions from aqueous solution. This capture process is reversible; that is, an ion adsorbed by a zeolite can generally be driven off again by heat. This property allows many zeolite-based molecular sieves to be reused indefinitely. Such sieves—often consisting of tanks filled with tons of crushed zeolitic tuff—have been used to filter radioactive cesium and strontium from nuclear waste, to remove ammonia from sewage, to scrub sulfur dioxide (SO_2) from coal-fired electric power station emissions, to purify landfill gas for household utility use, to filter mercury and other heavy **metals** from industrial wastewater, to remove calcium from water in water-softening systems, and for many other purposes.

Zeolites were first identified in 1756, but their molecular sieve properties were not observed until the mid 1920s. Even then they remained a mere curiosity for some time, as geologists still argued that natural zeolites were too rare to be commercially useful. Attention turned instead to zeolite synthesis. It was not until the 1950s that geologists discovered that million-ton deposits of volcanic **tuff** consisting mostly of zeolite are not, in fact, uncommon.

See also Crystals and crystallography; Minerology

SOURCES CONSULTED

Books

Abell, G., and D. Morrison. *Explorations of the Universe.* New York: Saunders College Publishing, 1987.

Adams, Charles K. *Nature's Electricity.* Blue Ridge Summit, PA: TAB Books, Inc., 1987.

Adams, Frank. *The Birth and Development of the Geological Sciences.* Mineola, New York: Dover Publications, Inc., 1954.

Ager, D. V. *The Nature of the Stratigraphic Record*. 2nd ed. New York: John Wiley and Sons, 1981.

Ahrens, C. D. *Essentials of Meteorology. An Invitation to the Atmosphere.* West Publishing Company, 1993.

Ahrens, C. D. *Meteorology Today: An Introduction to Weather, Climate and the Environment.* 4th ed. West Publishing Company, 1991.

Albritton Jr., C.C., ed. *Uniformity and Simplicity: A Symposium on the Principle of the Uniformity of Nature.* Boulder: Geological Society of America, 1967.

Alic, Margaret. *Hypatia's Heritage: A History of Women in Science from Antiquity through the Nineteenth Century.* Boston: Beacon Press, 1986.

Allegre, Claude J. *The Behavior of the Earth: Continental and Seafloor Mobility.* Cambridge: Harvard University Press, 1989.

Allen, Gary A. *Transition and Mixing in Axisymmetric Jets and Vortex Rings.* Washington: NASA, 1986.

Aller, Lawrence H. *Atoms, Stars, and Nebulae.* 3rd ed. Cambridge: Cambridge University Press, 1991.

American Men & Women of Science 1995-6. 19th ed. New Providence, New Jersey: R. R. Bowker, 1994, p. 618.

American Men and Women of Science: A Biographical Directory of Today's Leaders in Physical, Biological, and Related Sciences, 1998-99. 20th ed. New Providence, NJ: R. R. Bowker, 1998.

American Meteorological Society. *Challenges of Our Changing Atmosphere—Careers in Atmospheric Research and Applied Meteorology.* 1993.

American Water Works Association. *Water Quality and Treatment.* 5th ed. Denver: American Water Works Association, 1999.

Andrews, J. E., et. al. *An Introduction to Environmental Chemistry.* Blackwell Science.

Armstead, Christopher H., ed. *Geothermal Energy.* Paris: UNESCO, 1973.

Arnowitt, R. *Gravitation—An Introduction to Current Research*. London: Academic Press, 1977.

Asimov, Isaac. *The History of Physics.* New York: Walker and Company, 1966.

Asimov, Isaac. *Biographical Encyclopedia of Science and Technology.* New York: Avon Books, 1972.

Asimov, Isaac. *Asimov's Chronology of Science and Discovery.* New York: Harper & Row Publishers, 1989.

Atherly, A. G., J. R. Girton, and J. F. McDonald. *The Science of Genetics*. Fort Worth, TX: Saunders College Publishing, 1999.

Atkins, P. W. *Molecular Quantum Mechanics.* 2nd ed. Oxford: Oxford University Press, 1983.

Atkins, P. W. *Physical Chemistry.* 6th ed. Oxford: Oxford University Press, 1997.

Atkins, P. W. *Quanta: A Handbook of Concepts.* 2nd ed. Oxford: Oxford University Press, 1991.

Azaroff, Leonid V. *Elements of X-Ray Crystallography.* New York: McGraw-Hill Book Company, 1968.

Bailey Jr., Philip S., and Christina A. Bailey. *Organic Chemistry: A Brief Summary of Concepts and Applications.* 4th ed. Englewood Cliffs, NJ: Prentice Hall, 1989.

Banda, M. Torne, and M. Talwani. *Rifted Ocean-Continent Boundaries.* Kluwer Academic Publishers, 1987.

Barnes, J. *Basic Geological Mapping.* 3rd ed. New York: John Wiley and Sons, 1995.

Barnes-Svarney, Patricia, ed. *Science Desk Reference.* New York: Macmillan, 1995.

Barrow, John D. *The Origin of the Universe.* New York: Basic Books, 1994.

Barry, R. G., and R. J. Chorley. *Atmosphere, Weather, and Climate.* London: Methuen and Co., Ltd., 1971.

Bates, R., and J. Jackson, eds. *Dictionary of Geological Terms.* 3rd ed. New York: Anchor Books, 1984.

Bates, R. L., and J. A. Jackson. *Dictionary of Geological Terms.* New York: Doubleday, 1984.

Bates, R. L., and J. A. Jackson, eds. *Glossary of Geology.* 2nd ed. Falls Church, VA: American Geological Institute, 1980.

Battey, M. H., and A. Pring *Mineralogy for Students.* Harlow, Longman, 1997.

Battison, Edwin A. “Harrison, John.” vol. 6, *Dictionary of Scientific Biography.* Farmington Hills, MI: Macmillan Reference USA, 1981.

Bear, Jacob. *Dynamics of Fluids in Porous Media*. New York: Dover Publications, 1988.

Beckett, B. *Introduction to Cryptology.* Malden, Massachusetts: Blackwell Scientific, 1988.

Berggren, W. A., and J. A. Van Couvering, eds. *Catastrophes and Earth History, the New Uniformitarianism.* Princeton: Princeton University Press, 1984.

Berry, L., and B. Mason. *Mineralogy.* San Francisco: W. H. Freeman and Company, 1959.

Berry, W. B. N. *Growth of a Prehistoric Time Scale Based on Organic Evolution.* Revised edition. Oxford: Blackwell Scientific Publications, 1987.

Best, M. G. *Igneous and Metamorphic Petrology.* San Francisco: W. H. Freeman and Company, 1982.

Bettelheim, Frederick A., and Jerry March. *Introduction to General, Organic, & Biochemistry.* Philadelphia: Saunders College Publishing, 1983.

Billings, Marland P. *Structural Geology.* 3rd ed. Englewood Cliffs, New Jersey: Prentice-Hall, 1972.

Binney, James, and Michael Merrifield. *Galactic Astronomy.* Princeton, New Jersey: Princeton University Press, 1998.

Biographical Encyclopedia of Science. 2nd ed. Philadelphia: Lorenz, 1994.

Birkeland, Peter W. *Soils and Geomorphology*. New York: Oxford University Press, 1984.

Blackburn, William H., and William H. Dennen *Principles of Mineralogy.* Dubuque, IA: William C. Brown Publishers, 1988.

Blaedel, Niels. *Harmony and Unity.* Translated by Geoffrey French. Madison, Wisconsin: Science Tech, 1988.

Bland, W., and Rolls D. *Weathering, an Introduction to Scientific Principles.* New York: Oxford University Press, 1988.

Blatt, H. *Sedimentary Petrology.* New York: W. H. Freeman and Company, 1992.

Blatt, H., and R. J. Tracy. *Petrology: Igneous, Sedimentary, and Metamorphic.* New York: W. H. Freeman and Company, 1996.

Bless, R. C. *Introductory Astronomy.* Sausalito, CA: University Science Books, 1996.

Bloom, A. L. *Geomorphology: A Systematic Analysis of Late Cenozoic Landforms*. 2nd ed. Englewood Cliffs: Prentice Hall, 1991.

Bloss, F. D. *Crystallography and Crystal Chemistry*. New York: Holt, Rinehart and Winston, Inc., 1971.

Bockris, John O’M., and Amulya K. N. Reddy. *Modern Electrochemistry.* New York: Plenum Press, 1973.

Boggs, S. *Petrology of Sedimentary Rocks.* Paramus, NJ: Macmillan Publishing, 1992.

Bohr, Niels. *The Unity of Knowledge.* New York: Doubleday & Co., 1955.

Boorse, Henry A., Lloyd Motz, and Jefferson Hane Weaver. *The Atomic Scientists: A Biographical History.* New York: John Wiley & Sons, Inc., 1989.

Boorstin, Daniel J. *The Discoverers.* New York: Random House, 1983.

Bothun, Greg. *Modern Cosmological Observations and Problems.* London: Taylor & Francis Ltd., 1998.

Boyer, Rodney. *Concepts in Biochemistry.* Pacific Grove, CA: Brooks/Cole Publishing Company, 1999.

Boyle, Robert H., and R. Alexander Boyle. *Acid Rain.* New York: Schocken, 1983.

British Petroleum—Fifty Years in Pictures. London: British Petroleum, 1959.

Brock, William H. *The Norton History of Chemistry.* New York: W. W. Norton & Company, 1992.

Bronowski, J. *The Ascent of Man.* New York: Little, Brown & Co., 1984.

Brown, Julian. *Minds, Machines, and the Multiverse: The Quest for the Quantum Computer.* New York: Simon & Schuster, 2000.

Brownlow, A. *Geochemistry.* Englewood Cliffs, NJ: Prentice Hall Inc., 1997.

Bruice, Paula Y. *Organic Chemistry.* Englewood Cliffs, NJ: Prentice-Hall, Inc., 1995.

Bryan, T. Scott. *The Geysers of Yellowstone.* Boulder, CO: Colorado Associated University Press, 1986.

Bugayevskiy, Lev M., and John P. Snyder. *Map Projections: A Reference Manual*. London: Taylor and Francis, 1995.

Burchfield, J. D. *Lord Kelvin and the Age of the Earth.* Chicago: University of Chicago Press, 1990.

Burk, C. A., and C. L. Drake. *The Geology of Continental Margins.* New York: Springer-Verlag, 1974.

Burke, James. *The Day the Universe Changed.* Boston: Little, Brown and Company, 1985.

Bynum, W. F., E. J. Browne, and Roy Porter, eds. *Dictionary of the History of Science.* Princeton, NJ: Princeton University Press, 1984.

Campbell, A. M. “Monoclonal Antibodies.” In *Immunochemistry*, edited by Carol J. van Oss and Marc H. V. van Regenmortel. New York: Marcel Dekker, Inc., 1994.

Carmichael, I., F. Turner, and J. Verhoogen. *Igneous Petrology.* New York: McGraw-Hill Book Company, 1974.

Carozzi, Albert V. “Guyot, Arnold Henri.” Vol. 5, *Dictionary of Scientific Biography*. Farmington Hills, MI: MacMillan Reference USA, 1981.

Carroll, Bradley W., and Dale A. Ostlie. *An Introduction to Modern Astrophysics.* Reading, MA: Addison-Wesley Publishing Company, Inc., 1996.

Carroll, Felix A. *Perspectives on Structure and Mechanism in Organic Chemistry.* Pacific Grove, CA: Brooks/Cole Publishing Company, 1998.

Carswell, D. A., ed. *Eclogite Facies Rocks.* Glasgow: Blackie, 1999.

Cattermole, Peter, and Patrick Moore. *The Story of the Earth.* Cambridge: Cambridge University Press, 1985.

Chaisson, Eric J. *The Hubble Wars: Astrophysics Meets Astropolitics in the Two-Billion-Dollar Struggle over the Hubble Space Telescope.* London: Harvard University Press, 1994.

Chow, Ven T., et al. *Applied Hydrology*. New York: McGraw Hill, 1988.

Christiansen, E. H, and W. K. Hamblin. *Exploring the Planets.* 2nd ed., Englewood Cliffs, NJ: Prentice Hall, 1995.

Clifford, Martin. *Basic Electricity & Beginning Electronics.* Blue Ridge Summit, PA: TAB Books, 1973.

Cline, William R. *The Economics of Global Warming.* Washington: Institute for International Economics, 1992.

Cobb, Cathy, and Harold Goldwhite. *Creations of Fire: Chemistry’s Lively History from Alchemy to the Atomic Age.* New York: Plenum Press, 1995.

Collings, Peter J. *Liquid Crystals: Nature’s Delicate Phase of Matter.* Princeton: Princeton University Press, 1990.

Colman, S., and D. P. Dethier. *Rates of Chemical Weathering of Rocks and Minerals.* Academic Press, 1996.

Compton, R. R. *Geology in the Field.* New York: Wiley and Sons, 1992.

Conant, James B. *The Overthrow of the Phlogiston Theory: The Chemical Revolution of 1775–1789.* Cambridge: Harvard University Press, 1966.

Connors, Kenneth. *Chemical Kinetics: The Study of Reaction Rates in Solution.* New York: VCH, 1990.

Cooke, R. U., and J. C. Doornkamp. *Geomorphology in Environmental Management*. 2nd ed. Oxford, UK: Clarendon Press, 1990.

Cooper, J. D., R. H. Miller, and J. Patterson. *A Trip Through Time: Principles of Historical Geology.* Columbus, OH: Merrill Publishing Company, 1990.

Cotton, F. Albert. *Advanced Inorganic Chemistry: A Comprehensive Text.* 2nd ed. New York: Interscience Publishers, 1966.

Cottrell, A. *An Introduction to Metallurgy.* 2nd ed. London: Edward Arnold, 1975.

Coughlan, G. D., and J. E. Dodd. *The Ideas of Particle Physics*. 2nd ed. Cambridge: Cambridge University Press, 1991.

Coulomb, J. *Sea Floor Spreading and Continental Drift.* Dordrecht, Netherlands: D. Reidel Publishing Co., 1972.

Cragg, G. R. *Reason and Authority in the Eighteenth Century.* London: Cambridge University Press, 1964.

Creese, M. R. S., and T. M. Creese. *Ladies in the Laboratory, American and British Women in Science 1800–1900.* London: The Scarecrow Press Inc., 1998.

Cutnell, John D., and Johnson, Kenneth W. *Physics*. 4th ed. New York: John Wiley & Sons, 1998.

Dainith, John, ed. *A Dictionary of Chemistry.* 3rd ed. Oxford: Oxford University Press, 1996.

Dainith, John, Sarah Mitchell, Elizabeth Tootill, and Derek Gjertsen, eds. *Biographical Encyclopedia of Scientists.* 2nd ed. Bristol, UK: Institute of Physics Publishing, 1994.

Dalrymaple, G. B. *Rock Magnetics Laboratory Upper Mantle Project, United States Program.* Washington: National Academy of Science, 1971.

David, G. H. *Structural Geology of Rocks and Regions.* New York: John Wiley & Sons Inc., 1984.

Davies, Paul, and John Gribbin. *The Matter Myth: Dramatic Discoveries that Challenge Our Understanding of Physical Reality.* New York: Touchstone Books, 1992.

Davies, Paul. *The Last Three Minutes.* New York: Basic Books, 1994.

Davies, Paul. *The Mind of God.* New York: Simon & Schuster, 1992.

Davies, Paul A. *The New Physics.* Cambridge: Cambridge University Press, 1989.

Davies, Paul A. *Mechanisms of Continental Drift and Plate Tectonics.* London: Academic Press, 1980.

Davis, N. *Permafrost: A Guide to Frozen Ground in Transition.* Fairbanks, Alaska: University of Alaska Press, 2001.

Davis, R. A. *Depositional Systems.* 2nd ed. Englewood Cliffs, New Jersey: Prentice Hall, 1992.

Davis, Raymond E., H. Clark Metcalfe, John E. Williams, and Joseph F. Castka, eds. *Modern Chemistry.* Austin, TX: Holt, Rinehart and Winston, Inc., 1999.

Dawson, J. B. *Kimberlites and Their Xenoliths*. Berlin: Springer-Verlag, 1980.

Dawson, J. B. “New Aspects of Diamonds Geology.” In *The Properties of Diamond*, edited by D. Fields. London: Academic Press, 1979: 539–554.

Deason, G. B. *Reformation Theology and the Mechanistic Conception of Nature, in God and Nature*. Edited by D. C. Lindberg and R. L. Numbers. University of California Press, 1986.

Deer, W. A., R. A. Howie, and J. Zussman *An Introduction to the Rock-Forming Minerals.* New York: Longman Scientific and Technical, 1994.

Delgass, W. Nicholas, Gary L. Haller, Richard Kellerman, and Jack H. Lunsford, eds. *Spectroscopy in Heterogeneous Catalysis.* New York: Academic Press, 1979.

Dessler, A. *The Chemistry and Physics of Stratospheric Ozone.* Cornwall, UK: Academic Press, 2000.

Dewey, J. F., and G. M. Kay. “Appalachian and Caledonian Evidence for Drift in the North Atlantic.” In *History of the Earth’s Crust.* Princeton: Princeton University Press, 1968.

Dolgoff, A. *Essentials of Physical Geology*. Boston: Houghton Mifflin, 1998.

Donn, William L. *Meteorology.* 4th ed. New York: McGraw-Hill Book Company, 1975.

Doyle P., and M. B. Bennett *The Key To Earth History.* John Wiley and Sons, 1994.

Driscoll, F. *Groundwater and Wells.* 2nd ed. St. Paul: Johnson Filtration Systems, Inc., 1989.

Duff, P. *Holmes’ Principles of Physical Geology.* 4th ed. New York: Chapman & Hall, 1993.

Duffin, W. J. *The Solid State: From Superconductors to Superalloys.* Translated by André Guinier and Rémi Jullien. Oxford: Oxford University Press, 1989.

Dunlop, D. J., and Ö. Özdemir, *Rock Magnetism—Fundamentals and Frontiers.* Cambridge: Cambridge University Press, 1997.

DuToit, A. L. *Our Wandering Continents: An Hypothesis of Continental Drifting.* New York: Hafner Publishing Company, 1937.

Eardley, A. J. *Structural Geology of North America.* New York: Harper Brothers, 1951.

Ebbing, Darrell D., and Steven D. Gammon. *General Chemistry.* 6th ed. Boston: Houghton Mifflin Company, 1999.

Ehlers, E., and H. Blatt. *Petrology: Igneous, Sedimentary, and Metamorphic.* San Francisco: W. H. Freeman and Company, 1980.

Elliott, W. H., and D. C. Elliott. *Biochemistry and Molecular Biology.* New York: Oxford University Press, 1997.

Ellis, G. F. R., and R. M. Williams. *Flat and Curved Space-Times.* Oxford: Clarendon Press, 2000.

Elmegreen, Debra Meloy. *Galaxies and Galactic Structure.* Upper Saddle River, NJ: Prentice Hall, 1998.

Elschenbroich, Christoph, and Albrecht Salzer. *Organometallics: A Concise Introduction.* 2nd ed. New York: VCH, 1992.

Elsom, D. *Earth: The Making, Shaping and Workings of a Planet.* New York: Macmillian and Company, 1992.

Emiliani, Cesare. *Planet Earth: Cosmology, Geology, and the Evolution of Life and the Environment.* Cambridge: Cambridge University Press, 1992.

Epstein, Lewis Carroll. *Relativity Visualized.* San Francisco: Insight Press, 1997.

Erwin, D. H. *The Great Paleozoic Crisis: Life and Death in the Permian.* New York: Columbia University Press, 1993.

Evans, A. M. *An Introduction to Economic Geology and its Environmental Impact.* Malden, MA: Blackwell Science, 1997.

Ewing, Galen W. *Instrumental Methods of Chemical Analysis.* 4th ed. New York: McGraw-Hill Book Company, 1975.

Eyles, Joan M. “Smith, William.” Vol. 12, *Dictionary of Scientific Biography,* edited by C. C. Gillispie. New York: Charles Scribner & Sons, 1975, pp. 486-492.

Fairbridge, Rhodes, ed. *Encyclopedia of Sedimentology.* Stroudsburg, PA: Dowden, Hutchison, and Ross, 1978.

Farndon, J., *Dictionary of the Earth*. New York: Dorling Kindersley Publishing, Inc., 1994.

Felder, D. *The 100 Greatest Women of All Time*. Oxford: Past Times, 1997.

Feldman, Anthony, and Peter Ford. *Scientists & Inventors.* New York: Facts on File, 1979.

Ferris, Timothy, ed. *The World Treasury of Physics, Astronomy and Mathematics.* Boston: Little, Brown and Company, 1991.

Feynman, Richard P. *QED: The Strange Theory of Light and Matter.* Princeton: Princeton University Press, 1985.

Feynman, Richard P. *The Character of Physical Law.* Cambridge: MIT Press, 1965.

Feynman, Richard. *The Feynman Lectures on Physics.* Vol. 1. Reading, MA: Addison-Wesley Publishing Company, 1963.

Fieser, Louis F., and Mary Fieser. *Textbook of Organic Chemistry.* Boston: D. C. Heath and Company, 1950.

Fike, D. J. "Immunoglobulin Structure and Function." In *Clinical Immunology: Principles and Laboratory Diagnosis*. 2nd edition. Edited by Catherine Sheehan. Philadelphia: Lippincott-Raven Publishers, 1997.

Fischer, Daniel, and Hilmar Duerbeck. *Hubble: A New Window to the Universe.* Translated by Helmut Jenkner and Douglas Duncan. New York: Copernicus, 1996.

Fischer, G., and G. Wefer. *Use of Proxies in Paleoceanography*. Berlin Heidelberg: Springer-Verlag, 1999.

Fisher, David E. *Fire and Ice: The Greenhouse Effect, Ozone Depletion, and Nuclear Winter.* New York: Harper & Row, 1990.

Fisher, Robert L., and Roger Revelle "The Trenches of the Pacific." In *Continents Adrift: Articles from Scientific American 1972–1970,* edited by J. T. Wilson. New York: W. H. Freeman and Co., 1975.

Flaste, Richard, ed. *What Everyone Needs to Know from Newton to the Knuckleball*. New York: Times Books/Random House, 1991.

Flint, R. *Glacial Geology and the Pleistocene Epoch.* New York: John Wiley & Sons, 1949.

Foster, James, and J. D. Nightingale. *A Short Course in General Relativity.* New York: Springer-Verlag, 1995.

Francis, P. *Volcanoes: A Planetary Perspective.* New York: Oxford University Press, 1993.

Fraser, P. M. *Ptolemaic Alexandria.* Oxford: Clarendon Press, 1972.

Freeman, Ira M. *Physics Made Simple.* New York: Doubleday, 1990.

Freeman, T. *Procedures in Field Geology.* Boston: Blackwell Science, Inc., 1999.

Freeze, R., and J. Cherry. *Groundwater.* Englewood Cliffs: Prentice-Hall, Inc., 1979.

French, A. P. *Special Relativity.* New York: W. W. Norton & Company, 1968.

French, B. M. *Traces of Catastrophe.* Houston: Lunar and Planetary Institute, 1999.

Freund, R. *A Dynamic Model of Subduction Zones.* Jerusalem: Hebrew University of Jerusalem, 1991.

Frick, Thomas C. *Petroleum Production Handbook.* Vol. 1. Dallas: Society of Petroleum Engineers of AIME, 1962.

Friend, J. Newton. *Man and the Chemical Elements: An Authentic Account of the Successive Discovery and Utilization of the Elements From the Earliest Times to the Nuclear Age.* 2nd ed. New York: Charles Scribner's Sons, 1961.

Frisch, Otto R. *The Nature of Matter*. New York: E. P. Dutton, 1972.

Fritz, W., and J. Moore. *Basics of Physical Stratigraphy and Sedimentology.* New York: John Wiley & Sons, 1988.

Gaia: A New Look at Life on Earth. Oxford: Oxford University Press, 1995.

Galeotti, P., and David N. Schramm, eds. *Dark Matter in the Universe.* Dordrecht, The Netherlands. Kluwer Academic Publishers, 1990.

Galloway, W. E., and D. K. Hobday *Terrigenous Clastic Depositional Systems.* Berlin: Springer-Verlag, 1996.

Garrity, John A., and Mark C. Carnes, eds. *American National Biography.* New York: Oxford University Press, 1999.

Gaskell, T. F. *The Earth's Mantle.* New York: Academic Press, 1967.

Gavin, Sir William. *Ninety Years of Family Farming: The Story of Lord Rayleigh's and Strutt & Parker Farms.* London: Hutchinson, 1967.

George, Wilma, and Rene Lavocat. *The African-South America Connection*. New York: Oxford University Press, 1993.

Ghosh S. K. *Structural Geology: Fundamentals and Modern Developments*. Oxford, New York: Pergamon Press, 1993.

Giancoli, Douglas C. *Physics: Principles with Applications.* 5th ed. New Jersey: Prentice Hall, 1998.

Gile, L. H., et al. *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico: A Guidebook to the Desert Project.* Socorro: New Mexico Bureau of Mines and Mineral Resources, 1981.

Gillispie, Charles Coulston, ed. *Dictionary of Scientific Biography*. New York: Charles Scribner's Sons, 1981.

Gilmore, Robert. *Alice in Quantumland*. New York: Copernicus Books, 1995.

Gittwitt, Paul G. *Conceptual Physics.* 6th ed. New York: HarperCollins Publishers, 1989.

Gleick, James. *Chaos.* New York: Penguin, USA, 1988.

Glennie, K. W. *Desert Sedimentary Environments: Developments in Sedimentology.* Vol 14, enclosure 4. New York: American Elsevier Publishing Co, 1970.

Goldman, Martin. *The Demon in the Aether, The Story of James Clerk Maxwell.* Edinburgh: Paul Harris Publishing, 1983.

Goldsmith, Donald. *Einstein's Greatest Blunder? The Cosmological Constant and other Fudge Factors in the Physics of the Universe.* Cambridge: Harvard University Press, 1995.

Golub L., and J. M. Pasachoff. *The Solar Corona.* Cambridge: Cambridge University Press, 1997.

Goodman, H. Maurice. *Basic Medical Endocrinology.* 2nd ed. New York: Raven Press, 1994.

Gould, Stephen Jay. *Ever Since Darwin.* New York: W. W. Norton, 1977.

Goyer, R. A. "Toxic Effects of Metals." In *Casarett and Doull's Toxicology: The Basic Science of Poisons.* 5th ed. New York: McGraw-Hill Companies, Inc., 1996.

Gray, H. J., and Alan Isaacs. *The Penguin Dictionary of Physics.* Middlesex, UK: Penguin, 1977.

Greeley, R., and R. Batson. *The NASA Atlas of the Solar System.* New York: Cambridge University Press, 1996.

Greeley, R., and R. M. Batson. eds. *Planetary Mapping.* New York: Cambridge University Press, 1990.

Green, James A. *Letters on Unified Field Theory: From General Relativity to Unified Field Theory.* Hollywood Greenwood Research, 1999.

Greene, Brian. *The Elegant Universe.* New York: W. W. Norton and Company, 1999.

Gribbin, John. *Q is for Quantum: An Encyclopedia of Particle Physics.* New York: The Free Press, 1998.

Gribbin, John. *Schrodinger's Kittens and the Search for Reality.* London: Weidenfield & Nicholson, 1995.

Grider, R. W. *Continental Drift: Some Boundary Conditions from Surface Phenomena.* London: Academic Press, 1983.

Grimal, Nicolas. *A History of Ancient Egypt.* Cambridge: Blackwell, 1992.

Guilbert, J. M., and C. F. Park. *The Geology of Ore Deposits.* New York: W. H. Freeman, 1986.

Haan, C. T., et al. *Design Hydrology and Sedimentology for Small Catchments*. San Diego: Academic Press, 1994.

Hall A. *Igneous Petrology.* Essex, England: Longman Group Limited, 1996.

Hall, C. *Gemstones.* New York: DK Publishing Inc., 1994.

Hamblin, W. K., and E. H. Christiansen. *Earth's Dynamic Systems.* 9th ed. Upper Saddle River: Prentice Hall, 2001.

Hamblyn, Richard. *The Invention of Clouds: How an Amateur Meteorologist Forged the Language of the Skies*. New York: Farrar, Straus and Giroux, 2001.

Hamermesh, Morton. *Group Theory and its Application to Physical Problems.* New York: Dover Publications, Inc., 1989.

Hancock, P. L., and B. J. Skinner, eds. *The Oxford Companion to the Earth.* New York: Oxford University Press, 2000.

Harland W. B., et al. *A Geologic Time Scale.* New York: Cambridge University Press, 1990.

Harre, Rom. *Great Scientific Experiments: Twenty Experiments that Changed Our View of the World.* Oxford: Phaidon Press Limited, 1981.

Harrold, Frances B., and Raymond A. Eve, eds. *Cult Archaeology and Creationism: Understanding Pseudoscientific Beliefs about the Past*. University of Iowa Press, 1987.

Hawking, Stephen. *A Brief History of Time: From the Big Bang to Black Holes.* New York: Bantam, 1988.

Heezen, B. C. "The Deep Sea-Floor." In *Continenal Drift,* edited by S. K. Runcorn. New York: Academic Press, 1962.

Heezen, B. C. *The Face of the Deep.* Oxford: Oxford University Press, 1971.

Heinrich, W. *Microscopic Identification of Minerals.* St. Louis: McGraw-Hill, Inc., 1965.

Heiserman, David L. *Exploring Chemical Elements and Their Compounds.* Blue Ridge Summit, PA: TAB Books, 1992.

Hellemans, Alexander, and Bryan Bunch. *The Timetables of Science: A Chronology of the Most Important People and Events in the History of Science.* New York: Simon & Schuster Inc., 1988.

Henisch, Heinz K. *Crystal Growth in Gels.* University Park, PA: The Pennsylvania State University Press, 1970.

Hewitt, Paul G., John Suchocki, and Leslie A. Hewitt. *Conceptual Physics.* 3rd ed. Menlo Park, CA: Addison-Wesley, 1999.

Hill, C., and P. Forti. *Cave Minerals of the World.* 2nd ed. Huntsville: National Speleological Society, Inc., 1997.

Hilts, Philip J. *Scientific Temperaments: Three Lives in Contemporary Science.* New York: Simon & Schuster, 1982.

Hoffman, Robert V. *Organic Chemistry: An Intermediate Text.* New York: Oxford University Press, 1997.

Holland, C. H. *The Idea of Time.* New York: John Wiley and Sons, 1999.

Holmes, A. *Principles of Physical Geology.* London: Thomas Nelson & Sons, 1944.

Holmes, A. *The Age of the Earth.* London: Harper & Brothers, 1909.

Hough, Jack L. *Geology of the Great Lakes.* Urbana, IL: University of Illinois Press, 1958.

Howarth, S. *A Century in Oil.* London: Wiedenfeld & Nicholson, 1997.

Howells, W. W. "*Homo Erectus*—Who, When and Where: A Survey." In *The Human Evolution Source Book.* Englewood Cliffs, NJ: Prentice Hall, 1993.

Hoyt, D. V., and K. H. Schatten. *The Role of the Sun in Climate Change.* Oxford: Oxford University Press, 1997.

Hsü, K. *Challenger at Sea.* Princeton: Princeton University Press, 1992.

Huang, Kerson. *Statistical Mechanics.* New York: John Wiley & Sons, 1987.

Huang, W. T. *Petrology.* York, PA: McGraw-Hill Book Company, 1962.

Hudson, John. *The History of Chemistry.* New York: Chapman & Hall, 1992.

Hughes, R. I. G. *The Structure and Interpretation of Quantum Mechanics.* Cambridge: Harvard University Press, 1989.

Huizenga, John R. *Cold Fusion: The Scientific Fiasco of the Century.* Oxford: Oxford University Press, 1993.

Hunter, Robert J. *Introduction to Modern Colloid Science.* Oxford: Oxford Unversity Press, 1993.

Hurlbut, C. *Dana's Manual of Mineralogy.* 18th ed. New York: John Wiley & Sons, 1971.

Hurlbut, C. S., and C. Klein. *Manual of Mineralogy.* New York: John Wiley & Sons, Inc., 1977.

Hyndman, D. *Petrology of Igneous and Metamorphic Rocks.* Blacklick, OH: McGraw-Hill, 1985.

International Subcommission on Stratigraphic Classification (A. Salvador, chairman). *International Stratigraphic Guide.* 2nd ed. Boulder: Geological Society of America, 1994.

Interrante, Leonard V., Lawrence A. Caspar, and Arthur B. Ellis, eds. *Materials Chemistry: An Emerging Discipline.* Washington: American Chemical Society, 1995.

Irving, E. *Paleomagnetism and Its Application to Geological and Geophysical Problems.* New York: John Wiley & Sons, 1964.

Jackson, K. C. *Textbook of Lithology.* New York: McGraw-Hill Inc., 1970.

Jacobs, J. A. *Reversals of the Earth's Magnetic Field.* 2nd ed. Cambridge: Cambridge University Press, 1994.

Jaeger, J. C., and N. G. W. Cook. *Fundamentals of Rock Mechanics.* New York: Chapman and Hall, 1979.

Jahn, F., M. Cook, and M. Graham. *Hydrocarbon Exploration and Production. Developments in Petroleum Science.* Vol. 46. The Netherlands: Elsevier Science, 2000.

James, Laylin K, ed. *Nobel Laureates in Chemistry: 1901–1992.* American Chemical Society and the Chemical Heritage Foundation, 1993.

James, Preston Everett, and Geoffrey J. Martin, *All Possible Worlds: A History of Geographical Ideas*. 2nd ed. New York: Wiley, 1981.

Jeffery, Harold. *The Earth.* Cambridge: Cambridge University Press, 1970.

Johnson, A. M., with contributions by J. R. Rodine. "Debris Flow." In *Slope Instability*, edited by D. Brunsden and D. B. Prior. Chicester, UK: John Wiley & Sons, 1984.

Jolly, William L. *Modern Inorganic Chemistry.* New York: McGraw-Hill Book Company, 1984.

Jones, D. S. *Acoustic and Electromagnetic Waves.* Oxford: Clarendon Press, 1989.

Julien, Peirre Y. *Erosion and Sedimentation*. Cambridge: University Press, 1994.

Kamm, L. J. *Understanding Electro-Mechanical Engineering.* Piscataway, NJ: IEEE Press, 1995.

Kane, Gordon. *The Particle Garden: Our Universe as Understood by Particle Physicists.* Reading, MA: Helix Books, 1995.

Kaplan, D., and L. Glass. *Understanding Nonlinear Dynamics.* Berlin: Springer-Verlag, 1995.

Karrow, Robert W. *Mapmakers of the Sixteenth Century and Their Maps: Bio-Bibliographies of the Cartographers of Abraham Ortelius, 1570*. Chicago: Newberry Library, Speculum Orbis Press, 1993.

Kauffman, J. *Physical Geology.* 8th ed. Englewood Cliffs, NJ: Prentice Hall, Inc., 1990.

Kaufmann, William. *Black Holes and Warped Spacetime.* New York: W. H. Freeman and Company, 1979.

Kay, Marshall. *North American Geosynclines.* Geological Society of America, 1951.

Keller, E. A. *Introduction to Environmental Geology.* 2nd ed. Upper Saddle River: Prentice Hall, 2002.

Kelso, A. J. *Physical Anthropology.* 2nd ed. New York: Lippincott, 1974.

Kemp, T. S. *Fossils and Evolution.* Oxford: Oxford University Press, 1999.

Kempe, D. R. C. "Deep Ocean Sediments." *The Evolving* Earth, edited by L. R. M. Cocks. London: Cambridge University Press, 1981.

Kerr, P. *Optical Mineralogy.* 4th ed. New York: McGraw-Hill Book Company, 1977.

Kittel, Charles. *Introduction to Solid State Physics.* New York: John Wiley & Sons, 1996.

Kittel, Charles. *Thermal Physics.* New York: John Wiley & Sons, 1969.

Klein, C. *The Manual of Mineral Science.* 22nd ed. New York: John Wiley & Sons, 2002.

Klein, C., and C. S. Hurlbut Jr. *Manual of Minerology.* 20th ed. New York: John Wiley & Sons, 1985.

Kleinsmith, L. J., and V. M. Kish. *Principles of Cell and Molecular Biology.* 2nd ed. New York: HarperCollins College Publishers, 1995.

Klug, William S., and Michael R. Cummings. *Concepts of Genetics.* 5th ed. Upper Saddle River, NJ: Prentice-Hall, Inc., 1997.

Knighton, David. *Fluvial Forms & Processes.* New York: John Wiley & Sons, 1998.

Kock, Winston. *Lasers and Holography.* Mineola, New York: Dover Books, 1981.

Kondepudi, Dilip, and Ilya Prigogine. *Modern Thermodynamics: From Heat Engines to Dissipative Structures.* New York: John Wiley & Sons, 1998.

Krane, Kenneth S. *Modern Physics.* New York: John Wiley & Sons, 1983.

Krane, Kenneth. *Introductory Nuclear Physics.* New York: John Wiley & Sons, 1988.

Krapp, Kristine M., ed. *Notable Twentieth Century Scientists.* Detroit: The Gale Group, 1998.

Krauskopf K. B. *Introduction to Geochemistry.* New York: McGraw Hill, 1995.

Kummel, Bernhard. *History of the Earth: An Introduction to Historical Geology.* San Francisco: W. H. Freeman and Company, 1961.

Kurten, Bjorn. *Pleistocene Mammals of Europe.* Columbia: Columbia University Press, 1969.

Kurten, Bjorn. *The Age of Mammals.* Columbia: Columbia University Press, 1972.

Léna, Pierre. *Observational Astrophysics.* Translated by A. R. King. Berlin: Springer-Verlag, 1988.

Leakey, Richard, and Roger Lewin. *Origins Reconsidered: In Search of What Makes Us Human.* New York: Doubleday, 1992.

Leet, L. D., et al. *Physical Geology,* 4th ed. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1971.

LeGrand, H. E. *Drifting Continents and Shifting Theories: The Modern Revolution in Geology and Scientific Change.* London: Cambridge University Press, 1987.

LeMay, H. Eugene, Herbert Beall, Karen M. Robblee, and Douglas C. Brower, eds. *Chemistry: Connections to Our Changing World.* Teacher's Edition. Upper Saddle River, NJ: Prentice-Hall, Inc., 1996.

Leopold, Luna B., et al. *Fluvial Processes in Geomorphology.* New York: Dover Publications, 1995.

Leopold, Luna B. *A View of the River.* Cambridge: Harvard University Press, 1994.

LePichon, X. *Developments in Geotectonics, Plate Tectonics.* Amsterdam: Elsevier Scientific Publishing Co., 1973.

Lerner, Adrienne W. "Development of Trigonometry." In *Science and Its Times.* Vol. 3. Detroit: Gale Group, 2000.

Lerner, B. W. "Calculators, A Pocket-sized Revolution." *Science and Its Times.* Vol. 7. Detroit: Gale Group, 2000.

Lerner, K. L. "Bohr Theory." In *World of Chemistry*. Detroit: Gale Group, 1999.

Lerner, Rita G., and George L. Trigg, eds. *Encyclopedia of Physics.* 2nd ed. New York: VCH Publishers, Inc., 1991.

Levin H. L. *The Earth Through Time.* Saunders College Publishing, 1999.

Levine, Ira. *Quantum Chemistry.* 4th ed. New Jersey: Prentice Hall, 1991.

Lewis, C. L. E. *The Dating Game.* Cambridge: Cambridge University Press, 2000.

Lewis, Richard J., ed. *Hawley's Condensed Chemical Dictionary.* 13th ed. New York: Van Nostrand Reinhold, 1997.

Ley, Willy. *The Discovery of the Elements.* New York: Delacorte Press, 1968.

Liboff, Richard L. *Introductory Quantum Mechanics*. Reading, MA: Addison-Wesley Publishing Co., 1997.

Lide, D. R., and H. P. R. Frederikse, eds. *CRC Handbook of Chemistry and Physics 1996–1997: A Ready Reference Book of Chemical and Physical Data.* 77th ed. Boca Raton: CRC Press, 1996.

Lillesand, T. M., and R. W. Kiefer. *Remote Sensing and Image Interpretation.* 3rd ed. New York: John Wiley & Sons, Inc., 1994.

Linacre, E., and B. Geerts. *Climates and Weather Explained.* New York: Routledge, 1997.

Linklater, E. *The Voyage of the Challenger.* New York: Doubleday & Company, 1972.

Little, James Maxwell. *An Introduction to the Experimental Method: For Students of Biology and the Health Sciences.* Minneapolis: Burgess Publishing Co., 1961.

Lorenz, H. A., A. Einstein, H. Minkowski, and H. Weyl. *The Principle of Relativity.* Translated by W. Perrett and G. B. Jeffery. New York: Dover Publications, Inc., 1952.

Lovelock, James. *The Ages of Gaia: A Biography of Our Living Earth.* Revised and expanded edition. New York: W. W. Norton & Company, 1988.

Lowry, Thomas H., and Kathleen Schueller Richardson. *Mechanism and Theory in Organic Chemistry.* 3rd ed. New York: HarperCollins Publishers, Inc., 1987.

Luoma, Jon R. *Troubled Skies, Troubled Waters*. New York: Viking, 1984.

Lutgens F., and E. Tarbuck. *The Atmosphere.* 7th ed. New Jersey: Prentice Hall, Inc., 1998.

Lutgens, F. K., et. al. *Essentials of Geology.* 2nd ed. Columbus: Charles E. Merrill Publishing Co., 1986.

Maaloe S. *Principles of Igneous Petrology.* Berlin, New York: Springer-Verlag, 1985.

Manchester, R. N., and J. H. Taylor. *Pulsars.* San Francisco: W. H. Freeman, 1977.

Mandl, Franz. *Statistical Physics.* New York: John Wiley & Sons, 1988.

Margulis, Lynn, and Dorion Sagan. *Slanted Truths: Essays on Gaia, Symbiosis, and Evolution.* New York: Springer-Verlag, 1997.

Marsden, B. G., and A. G. W. Cameron. *The Earth-Moon System.* New York: Plenum Press, 1966.

Mascetta, Joseph A. *Chemistry the Easy Way.* 3rd ed. Barron's, 1996.

Mason, B., and C. B. Moore *Principles of Geochemistry.* New York: Wiley, 1982.

Mason, Stephen F. *Chemical Evolution: Origin of the Elements, Molecules, and Living Systems*. Oxford: Claredon Press, 1991.

Masterson, William L., and Emil J. Slowinski, eds. *Chemical Principles*. 4th ed. Philadelphia: W. B. Saunders Company, 1977.

Maton, Anthea, Jean Hopkins, Susan Johnson, David LaHart, Maryanna Quon Warner, and Jill D. Wright, eds. *Exploring Physical Science.* Teacher's Edition. Upper Saddle River, NJ: Prentice-Hall, Inc., 1999.

Maton, Anthea, et al. *Exploring Physical Science.* 3rd ed. New Jersey: Prentice Hall, 1999.

Matthews, Christopher K., and K. E. Van Holde, eds. *Biochemistry.* 2nd ed. New York: Benjamin/Cummings Publishing Company, 1966.

McConnell Jr., R. K. In "Viscosity of the Earth's Mantle." In *The History of the Earth's Crust: A Symposium*. Princeton: Princeton University Press, 1968.

McEvoy, G. K., ed. *AHFS Drug Information 1999.* Bethesda, MD: American Society of Health-System Pharmacists, Inc., 1999.

McGeary, D., and C. C. Plummer. *Physical Geology*. William C. Brown Publishers, 1992.

McIntyre, D. B., and A. McKirdy. *James Hutton: The Founder of Modern Geology.* Edinburgh: The Stationary Office Limited, 1997.

McKibben, Bill. *The End of Nature.* New York: Random House, 1989.

McPhee, John. *Basin and Range.* New York: Farrar, Straus, & Giroux, 1980.

McQuarrie, Donald A., and Peter A. Rock. *Descriptive Chemistry.* New York: W. H. Freeman and Company, 1985.

Melosh, H. J. *Impact Cratering, a Geologic Process.* New York: Oxford University Press, 1989.

Menard, H. *Geology, Resources, and Society.* San Francisco: W. H. Freeman and Company, 1974.

Menezes, A., P. van Oorschot, and S. Vanstone. *Handbook of Applied Cryptography.* Boca Raton: CRC Press, 1997.

Menzel, Donald H., ed. *Fundamental Formulas of Physics.* Mineola, NY: Dover Publications, 1960.

Merrill, R. T., M. W. McElhinny, and P. L. McFadden. *The Magnetic Field of the Earth, Paleomagnetism, the Core, and the Deep Mantle.* San Diego: Academic Press, 1996.

Merzbacher, E. *Quantum Mechanics.* New York: John Wiley & Sons, 1997.

Michaels, Patrick J. *Sound and Fury: The Science and Politics of Global Warming.* Washington: Cato Institute, 1992.

Michalas, D., and J. Binney. *Galatic Astronomy: Structure and Kinematics.* New York: W. H. Freeman and Co., 1981.

Middleton, Gerard V., and Peter R. Wilcock. *Mechanics in the Earth and Environmental Sciences*. Cambridge: Cambridge University Press, 1994.

Miller, E. Willard, and Ruby M. Miller. *Environmental Hazards: Air Pollution*. Santa Barbara: ABC-CLIO, 1989.

Misner, Charles, Kip Thorne, and John Archibald Wheeler. *Gravitation.* New York: W. H. Freeman and Company, 1973.

Mitton, Jacqueline, and Stephen P. Maran. *Gems of Hubble.* Cambridge: Cambridge University Press, 1996.

Miyashiro, A. *Metamorphic Petrology.* London: UCL Press, 1996.

Monroe, J. S., and R. Wicander. *Physical Geology: Exploring the Earth.* 3rd ed. Wadsworth Publishing Company, 1998.

Montanari, A., and C. Koeberl. *Impact Stratigraphy, the Italian Record.* Berlin: Springer-Verlag, 2000.

Montgomery, C. W., and D. Dathe. *Earth Then and Now.* William C. Brown Publishers, 1994.

Montgomery, C. W. *Environmental Geology.* 5th ed. McGraw Hill, 2000.

Moore G., and N. Sullivan. *Speleology, The Study of Caves*. St. Louis: Zephyrus Press, Inc., 1978.

Moore, C. A. *Handbook of Subsurface Geology*. New York: Harper & Row, 1963.

Moore, Walter John. *A Life of Erwin Schrodinger.* New York: Cambridge University Press, 1994.

Morris, Richard. *Time's Arrows: Scientific Attitudes Toward Time.* New York: Simon & Schuster, 1985.

Morrison, F. *The Art of Modeling Dynamic Systems: Forecasting for Chaos, Randomness, and Determinism.* New York: John Wiley & Sons, 1991.

Morrison, Robert Thornton, and Robert Neilson Boyd. *Organic Chemistry.* 5th ed. Boston: Allyn and Bacon, Inc., 1987.

Muir, Hazel, ed. *Larousse Dictionary of Scientists.* New York: Larousse Kingfisher Chambers, Inc., 1994.

Muir, J. *My First Summer in the Sierra.* Boston: Houghton Mifflin, 1911.

Muir, J. *Wilderness Essays.* Edited by F. Buske. Salt Lake City: Gibbs Smith, 1980.

Multhauf, Robert P. *The Origins of Chemistry.* London: Oldburne Book Co. ltd., 1966.

Nicolas, A. *The Mid-Oceanic Ridges.* Berlin: Springer-Verlag, 1995.

Nield, E. *Women and the Geological Society, A Report of the Working Group.* London: Geological Society of London, 1997.

Nilsson, Annika. *Greenhouse Earth.* Chichester: John Wiley & Sons, 1992.

North American Stratigraphic Code. Tulsa: American Association of Petroleum Geologists, 1983.

Nybakken, J. *Marine Biology: An Ecological Approach.* 4th ed. California: Addison-Wesley Educational Publishers, Inc., 1997.

O'Dunn, S., and W. D. Sill, *Exploring Geology, Introductory Laboratory Activities.* Needham Heights, MA: Ginn Press, 1993.

Ohanian, Hans. *Gravitation and Spacetime.* 2nd ed. New York: W. W. Norton & Company, 1994.

Olmstead, A. T. *Ancient Near East.* Chicago: University of Chicago Press, 1963.

Olmstead, A. T. *History of the Persian Empire and the Ancient MidEast.* Chicago: University of Chicago Press, 1959.

Olson, Donald W. "Gypsum." In *Minerals Yearbook.* Boulder: U.S. Geological Survey, 2000.

Orchin, M., and H. H. Jaffe. *Symmetry, Orbitals, and Spectra.* New York: Wiley-Interscience, 1971.

Ospovat, Alexander. "Werner, Abraham Gottlob." In *Dictionary of Scientific Biography.* Vol. 14, edited by C. C. Gillispie. New York: Charles Scribner and Sons, 1975, pp. 256-264.

Ostmann, Robert. *Acid Rain: A Plague Upon the Waters*. Minneapolis: Dillon, 1982.

Otoxby, David W., H. P. Gillis, and Norman H. Nachtrieb, eds. *The Principles of Modern Chemistry.* Fort Worth, TX: Harcourt Brace College Publishers, 1999.

Ottonello G. *Principles of Geochemistry.* New York: Columbia University Press, 1997.

Owen, H. G. "Constant Dimensions or an Expanding Earth?" In *The Evolving Earth,* edited by L. R. M. Cocks. London: Cambridge University Press, 1981.

Pais, Abraham. *Subtle is the Lord 1/4: The Science and the Life of Albert Einstein.* New York: Oxford University Press, 1982.

Pauling, Linus. *The Chemical Bond: A Brief Introduction to Modern Structural Chemistry.* Ithaca, NY: Cornell University Press, 1967.

Peierls, R. E. *Atomic History.* New York: Springer-Verlag, 1997.

Petersen, Carolyn Collins, and John C. Brandt. *Hubble Vision: Further Adventures with the Hubble Space Telescope.* 2nd ed. Cambridge: Cambridge University Press, 1998.

Peterson, M. N. A. *Initial Reports of the Deep Sea Drilling Project II.* Washington: Government Printing Office, 1970.

Pettijohn, F. J., P. E. Potter, and R. Siever. *Sand and Sandstone.* New York: Springer-Verlag, 1987.

Phinney, R. A., ed. *The History of the Earth's Crust.* Princeton: Princeton University Press, 1968.

Pinet, P. *Invitation to Oceanography.* Massachusetts: Joans and Bartlett Publishers, Inc., 1998.

Pitcher, Wallace S. *The Nature and Origin of Granite.* New York: Blackie Academic and Professional, 1993.

Pitzer, Kenneth S. *Thermodynamics.* 3rd ed. New York: McGraw-Hill, Inc., 1995.

Poole Jr., C. P. *The Physics Handbook: Fundamentals and Key Equations.* New York: John Wiley & Sons, 1998.

Popper, Karl R. *The Logic of Scientific Discovery.* New York: Basic Books, 1959.

Porter, Roy, and Marilyn Ogilvie, consultant eds. *The Biographical Dictionary of Scientists.* Vol. 2. New York: Oxford University Press, 2000.

Porter, Roy. *The Greatest Benefit to Mankind: A Medical History of Humanity.* New York: W. W. Norton & Company, Inc., 1997.

Press, F., and R. Siever. *Understanding Earth.* 3rd ed. New York: W. H. Freeman and Company, 2001.

Price, N. J., and J. W. Cosgrove. *Analysis of Geological Structures*. Cambridge: Cambridge University Press, 1990.

Proceedings of the Lunar Sample Symposium I. Houston: NASA Manned Spacecraft Center, 1972.

Proceedings of the Lunar Sample Symposium II. Houston: NASA Manned Spacecraft Center, 1973.

Proceedings of the Lunar Sample Symposium III. Houston: NASA Manned Spacecraft Center, 1975.

Proceedings of the Lunar Sample Symposium IV. Houston: NASA Manned Spacecraft Center, 1978.

Prothero, D. R. *Interpreting the Stratigraphic Record.* New York: W. H. Freedman and Company, 1990.

Prothro, D. R., and R. H. Dott Jr. *Evolution of the Earth.* 6th ed. Boston, McGraw-Hill, 2002.

Puddephatt, R. J., and P. K. Monaghan. *The Periodic Table of the Elements.* 2nd ed. Oxford: Clarendon Press, 1986.

Purser B., M. E. Tucker, and D. Zenger. *Dolomites*. International Associations of Sedimentologists, Special Publication No. 21. Oxford: Blackwell Scientific Publications, 1994.

Putnis, A. *Introduction to Mineral Sciences.* Hampshire, UK: Cambridge University Press, 1992.

Raguin, E. *Geology of Granite*. New York: Interscience Publishers, 1965.

Rayleigh, Lord (Robert John Strutt). *Life of John William Strutt, Third Baron Rayleigh.* Madison: University of Wisconsin Press, 1968.

Raymond L. A. *Petrology: The Study of Igneous, Sedimentary, and Metamorphic Rocks.* William C. Brown Publishers, 1995.

Rayner-Canham, Geoffrey, Arthur Last, Robert Perkins, and Mark van Roode. *Foundations of Chemistry.* Reading, PA: Addison-Wesley Publishing Company, 1983.

Reeder, R. J. *Carbonates: Mineralogy and Chemistry*. 2nd ed. Blacksburg, VA: Mineralogical Society of America, 1990.

Regional Geology of Africa. New York: Springer-Verlag, Inc., 1991.

Rhodes, Richard. *The Making of the Atomic Bomb.* New York: Touchstone/Simon & Schuster, 1986.

Rodman, Dorothy, Donald D. Bly, Fred Owens, and Ann-Claire Anderson. *Career Transitions for Chemists.* Salem: American Chemical Society, 1995.

Rodolico, Francesco. "Scilla, Agostino." In *Dictionary of Scientific Biography*, Vol. 12. 1975 pp. 256–257.

Rommer, A. S. *Vertebrate Paleontology*. Chicago: University of Chicago Press, 1966.

Ronchi, Vasco. *The Nature of Light: An Historical Survey.* Translated by V. Barocas. Cambridge, Massachusetts: Harvard University Press, 1970.

Rosenblum, Naomi. *A World History of Photography.* New York: Abbeville Press, 1997.

Rosser, W. G. V. *An Introduction to Statistical Physics.* New York: Prentice Hall, 1982.

Roth G. D. *Astronomy.* New York: Springer-Verlag, 1975.

Rozental, S., ed. *Niels Bohr: His Life and Work as Seen by Friends and Colleagues.* New York: John Wiley & Sons, 1967.

Rudwick, M. J. S. "Sedgwick, Adam." *Dictionary of Scientific Biography*. Vol. 12. 1975, pp. 275–279.

Runcorn, S. K. "Some Comments on Mechanism of Continental Drift." *Mechanisms of Contintntal Drift and Plate Tectonics.* New York: Academic Press, 1984.

Runcorn, S. K. *The Application of Modern Physics to the Earth and Planetary Interiors*. New York: Wiley-Interscience, 1969.

Russell, C. A., ed. *Recent Developments in the History of Chemistry.* London: The Royal Society of Chemistry, 1985.

Ryan, Charles W. *Basic Electricity: A Self-Teaching Guide,* 2nd ed. New York: John Wiley & Sons, Inc., 1986.

Sabins Jr., F. S. *Remote Sensing Principles and Interpretation.* 2nd ed. New York: W. H. Freeman and Company, 1987.

Sagan, Carl. *Cosmos.* New York: Random House, 1980.

Sakurai, J. J. *Advanced Quantum Mechanics.* Reading, MA: Addison-Wesley Publishing Company, 1967.

Salmon, Wesley C. *Space, Time, and Motion: A Philosophical Introduction.* Minneapolis: University of Minnesota Press, 1980.

Salzberg, Hugh W. *From Caveman to Chemist: Circumstances and Achievements.* Washington: American Chemical Society, 1991.

Sand, L. B., and F. A. Mumpton. *Natural Zeolites: Occurrence, Properties, Use.* London: Pergamon Press, 1978.

Sawkins F. J. *Metal Deposits in Relation to Plate Tectonics.* Berlin: Springer-Verlag, 1990.

Schneider, Stephen H., ed. *Scientists of Gaia.* Cambridge: The MIT Press, 1993.

Scholle, P., and D. Spearing, eds. *Sandstone Depositional Environments.* Tulsa: American Association of Petroleum Geologists, 1988.

Schwazbach, Martin. *Alfred Wegner, the Father of Continental Drift.* New York: Science Tech, 1986.

Schweber, Silvan S. *QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga.* Princeton: Princeton University Press, 1994.

Sciama, D. W. *Modern Cosmology and the Dark Matter Problem.* Cambridge: Cambridge University Press, 1993.

Science and Technology Department of the Carnegie Library of Pittsburgh. *The Handy Science Answer Book.* 2nd ed. Pittsburgh: The Carnegie Library of Pittsburgh, 1997.

Scientific Assessment of Ozone Depletion. Vols. I and II. World Meteorological Organization Global Ozone Research and Monitoring Project, 1988.

Scott, Stephen K. *Oscillations, Waves, and Chaos in Chemical Kinetics.* New York: Oxford University Press, 1994.

Sears, F. W., and G. L. Salinger. *Thermodynamics, Kinetic Theory and Statistical Thermodynamics.* Reading, MA: Addison-Wesley, 1975.

Seberry, J., and J. Pieprzyk. *Cryptography: An Introduction to Computer Security.* New York: Prentice Hall, 1989.

Selley, R. C. *Elements of Petroleum Geology.* San Diego: Academic Press, 1998.

Serway, Raymond A. *Physics for Scientists and Engineers with Modern Physics.* 3rd ed. Philadelphia: Saunders College, 1990.

Seyfert, C. K., and Leslie A. Sirkin. *Earth History and Plate Tectonics.* New York: Harper and Row Publishers, 1973.

Shapiro, Stuart L., and Saul A. Teukolsky. *Black Holes, White Dwarfs, and Neutron Stars.* New York: John Wiley & Sons, 1983.

Shapley, Harlow, and Helen E. Howarth. *A Source Book in Astronomy.* New York: McGraw-Hill, 1929.

Shipman, Harry. *Black Holes, Quasars, and the Universe.* New York: Houghton-Mifflin, 1976.

Shlain, Leonard. *Art and Physics: Parallel Visions in Space, Time, and Light.* New York: Quill, 1993.

Shorter, Edward. *The Health Century.* Doubleday, 1987.

Siever, R. *Sand*. New York: Scientific American Library, 1988.

Silk, J. *The Big Bang*. New York: W. H. Freeman and Co., 1980.

Simon, George P. *Ion Exchange Training Manual.* New York: Van Nostrand Reinhold, 1991.

Skinner, B. J., and S. C. Porter. *The Dynamic Earth.* 2nd ed. New York: John Wiley & Sons,1992.

Sklar, Lawrence. *Philosophy of Physics.* Boulder: Westview Press, 1992.

Slater, J. C. *Introduction to Chemical Physics.* New York: Dover Publications, Inc., 1939.

Sobel, Dava. *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*. London: Fourth Estate, 1995.

Soil Taxonomy. U.S. Department of Agriculture Handbook. Washington, DC: Government Printing Office, 1975.

Solomons, T., and W. Graham. *Fundamentals of Organic Chemistry.* 5th ed. New York: John Wiley & Sons, Inc., 1997.

Spencer, Edgar Winston. *Basic Concepts of Historical Geology.* New York: Thomas Y. Crowell Company, 1964.

Sperling, L. *Introduction to Polymer Science.* New York: John Wiley & Sons, Inc., 1992.

Spraycar, M., ed. *Stedman's Medical Dictionary.* 26th ed. Baltimore: Williams and Wilkens, 1995.

Stacey, F. D. *Physics of the Earth.* New York: John Wiley & Sons, 1969.

Stanley S. M. *Earth and Life Through Time.* W. H. Freeman and Company, 1986.

Starr, Cecie. *Biology: Concepts and Applications.* Belmont, CA: Wadsworth Publishing, 1997.

Starr, Chester G. *A History of the Ancient World.* New York: Oxford University Press, 1991.

Stewart, John A. *Drifting Continents and Colliding Paradigms.* Indiana University Press, 1990.

Stocchi, E. *Industrial Chemistry.* Vol. 1. Translated by K. A. K. Lott and E. L. Short. Chichester, West Sussex, UK: Ellis Horwood Limited, 1990.

Stokes, William Lee. *Essentials of Earth History.* Englewood Cliffs, NJ: Prentice-Hall, 1960.

Storey, T. Alabaster, and R. J. Pankhurst. *Magnetism & the Causes of Continental Break-Up.* American Association of Petroleum Geologists, 1992.

Strahler, A. *Physical Geology.* New York: Harper & Row, Publishers, 1981.

Strahler, A. N., and A. E. Strahler. *Modern Physical Geography.* New York: John Wiley & Sons, 1983.

Strangeway, D. W. *History of the Earth's Magnetic Field.* New York: McGraw-Hill Book Company, 1970.

Stroke, H. Henry, ed. *The Physical Review: The First Hundred Years.* Woodbury, New York: AIP Press, 1995.

Sullivan, J. A. *Continents in Motion.* New York: American Institute of Physics Press, 1990.

Swalin, Richard A. *Thermodynamics of Solids.* 2nd ed. New York: John Wiley & Sons, Inc., 1972.

Sykes, Lynn R. "Seismicity of the Mid Ocean Ridge System." In *The Earth's Crust and Upper Mantle: Geophysical Monograph*, no. 13. Washington: American Geophysical Union, 1969.

Tarbuck, E., and F. Lutgens. *The Earth: An Introduction to Physical Geology.* Columbus: Charles E. Merrill Publishing Company, 1984.

Tarling, D. *Continental Drift: A Study of the Earth's Moving Surface.* New York: Doubleday, 1971.

Taylor, A. W. B. *Superfluidity and Superconductivity.* 2nd ed. Bristol: Adam Hilger, 1986.

Taylor, Hugh S. *A Treatise on Physical Chemistry: A Co-operative Effort by a Group of Physical Chemists.* 2nd ed. New York: D. Van Nostrand Company, Inc., 1931.

Taylor, R. J. *Galaxies: Structure and Evolution.* London: Wykeham Publications Ltd., 1978.

The Kirk-Othmer Encyclopedia of Chemical Technology. 4th ed. New York: John Wiley & Sons, Inc., 1993.

The Oxford Dictionary of Biochemistry and Molecular Biology. Oxford: Oxford University Press, 1997.

Thompson, G. R., and J. T. Trunk. *Essentials of Modern Geology: An Environmental Approach.* Saunders College Publishing, 1994.

Thompson, R., and F. Oldfield. *Environmental Magnetism.* London: Allen & Unwin, 1986.

Thornbury, W. D. *Principles of Geomorphology.* 2nd ed. New York: John Wiley & Sons, Inc., 1969.

Thorne, Kip S. *Black Holes and Time Warps.* New York: Norton, 1994.

Tierney, Brian, and Sidney Painter. *Western Europe in the Middle Ages, 300-1475.* 5th ed. New York: McGraw-Hill, Inc., 1992.

Tilling, Heliker, et al. *Eruptions of Hawaiian Volcanoes: Past, Present, and Future.* Boulder: U.S. Geological Service, 1987.

Tipler, Paul. *Foundations of Modern Physics.* New York: Worth Publishers, Inc., 1969.

Tippens, Paul E. *Applied Physics.* 3rd ed. New York: Gregg Division, McGraw-Hill Book Company, 1984.

Tocci, Salvatore, and Claudia Viehland. *Chemistry: Visualizing Matter.* Annotated Teacher's Edition. Austin: Holt, Rinehart and Winston, Inc., 1996.

Tolman, C. F. *Ground Water.* New York: McGraw-Hill, 1937.

Tolstoy, Ivan. *James Clerk Maxwell, A Biography.* Chicago: University of Chicago Press, 1981.

Townsend, John S. *A Modern Approach to Quantum Mechanics.* New York: McGraw-Hill, 1992.

Trefil, J. *Space, Time, Infinity.* New York: Pantheon Books, 1985.

Trefil, J. *Encyclopedia of Science and Technology.* The Reference Works, Inc., 2001.

Trowbridge, A. C., ed. *Dictionary of Geological Terms*. New York: American Geological Institute, Doubleday and Company, 1962.

Tucker, M. E. *The Field Description of Sedimentary Rocks.* London: The Geological Society, 1982.

Turner, A. Keith, and Robert L. Schuster, eds. *Landslides: Investigation and Mitigation*. Washington: National Academy Press, 1996.

Twiss, Robert J., and Eldridge M. Moores. *Structural Geology*. New York: W. H. Freeman & Company, 1992.

Ultimate Visual Dictionary of Science. London: Dorling Kindersley Limited, 1998

Verhoogan, J., F. Turner, L. Weiss, and C. Wahrhaftig. *The Earth*. New York: Holt, Rhinehart, and Winston, Inc., 1970.

Verhoogen, J., et al. *The Earth*. New York: Holt, Rinehart and Wilson, Inc., 1970.

Voelkel, James R. *Johannes Kepler and the New Astronomy.* New York: Oxford University Press, 1999.

Von Herzen, R. P. "Present Status of Ocean Heat Flow Measurements." In *Physics and Chemistry of the Earth*. 6th ed. London: Pergamon Press, 1965.

Warfield, G., ed. *Solar Electric Systems.* New York: Springer-Verlag, 1984.

Warren J. *Evaporites: Their Evolution and Economics*. Blackwell Science, Oxford, 1999.

Washburn, S. L. "The Study of Race." In *The Human Evolution Source Book.* Englewood Cliffs: Prentice Hall, 1993.

Watkins, J., M. Bottino, and M. Morisawa. *Our Geological Environment.* Philadelphia: W. B. Saunders Company, 1975.

Weast, Robert C. *Handbook of Chemistry and Physics.* Cleveland: CRC Press, 1975.

Weaver, Jefferson Hane. *The World of Physics: A Small Library of the Literature of Physics from Antiquity to the Present.* New York: Simon and Schuster, 1987.

Webb, George E. *Tree Rings and Telescopes: The Scientific Career of A. E. Douglass.* Tucson: University of Arizona Press, 1983.

Wegener, Alfred. *The Origin of Continents and Oceans.* New York: Dover Publications, 1966.

Weinberg, S. *The First Three Minutes.* New York: Basic Books, 1977.

Weisburger, E. K. “General Principles of Chemical Carcinogenesis.” In *Carcinogenesis,* edited by M. P. Waalkes and Jerrold M. Ward. New York: Raven Press, Ltd., 1994.

Wells II, W. G. “The Effects of Fire on the Generation of Debris Flows in Southern California.” In *Debris Flows/Avalanches: Process, Recognition, and Mitigation,* edited by John E. Costa and Gerald F. Wieczorek. Boulder: Geological Society of America, 1987.

Wenninger, J. A., and G. N. McEwen Jr., eds. *International Cosmetic Ingredient Dictionary and Handbook.* 7th ed. Washington: The Cosmetic, Toiletry, and Fragrance Association, 1997.

Whalley, W. B. “Rockfalls.” In *Slope Instability,* edited by D. Brunsden and D. B. Prior. Chicester, UK: John Wiley & Sons, 1984, pp. 217–256.

Wheeler, J. A., and W. H. Zurek, eds. *Quantum Theory and Measurement.* Princeton: Princeton University Press, 1983.

White A. J. R., and B. W. Chappell. *Granitoid Types and Their Distribution in the Lachlan Fold Belt, Southeastern Australia.* Geological Society of America, 1983.

Whittaker, Edmund. *A History of Theories of Aether and Electricity.* New York: Dover Publications, Inc., 1989.

Willard, Hobart H., Lynn L. Merritt Jr., John A. Dean, and Frank A. Settle Jr. *Instrumental Methods of Analysis.* 7th ed. Belmont, CA: Wadsworth Publishing Company, 1988.

Williams, E. T., and C. S. Nicholls, eds. *The Dictionary of National Biography: 1961–1970.* New York: Oxford University Press, 1981.

Williams, H., and A. McBirney *Volcanology.* San Francisco: Freeman, Cooper & Co., 1979.

Williams, J. *The Weather Book.* New York: Vintage Books, 1992.

Williams, P., and M. Smith *The Frozen Earth: Fundamentals of Geocryology.* Oxford, UK: Cambridge University Press, 1989.

Williams, Trevor I., ed. *A Biographical Dictionary of Scientists.* 3rd ed. New York: John Wiley & Sons, Inc., 1982.

Wilson, J. T., ed. *Continents Adrift: Articles from Scientific American, 1972–1970.* New York: W. H. Freeman, 1975.

Winter, C. J., R. L. Sizmann, and L. L. Vant-Hull, eds. *Solar Power Plants.* New York: Springer-Verlag, 1991.

Wolfe, Drew H. *General, Organic, and Biological Chemistry.* New York: McGraw-Hill Book Company, Inc. 1986.

Women Geoscientists Committee. *Profile of Women Professional Geoscientists, Report of Questionnaire Findings.* American Geological Institute, 1977.

Woodhouse, N. M. J. *Special Relativity.* New York: Springer-Verlag, 1992.

Woolfson, M. M. *An Introduction to X-Ray Crystallography.* Cambridge: Cambridge University Press, 1970.

World Directory of Rocks and Minerals. Switzerland: Morges, 1987.

Yeomans, Donald K. *Comets: A Chronological History of Observation, Science, Myth, and Folklore.* New York: John Wiley & Sons, 1991.

Yergin, D. *The Prize.* New York: Simon and Schuster, 1991.

Zeilick, Michael, and Stephen A. Gregory. *Introductory: Astronomy and Astrophysics.* 4th ed. Orlando: Harcourt Brace & Company, 1998.

Zeldovich, Ya B., and Yu. P. Raizer. *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena.* San Diego: Academic Press, 1966.

Zitzewitz, Paul W., et al. *Merrill Physics: Principles and Problems.* Westerville, OH: Glencoe/McGraw-Hill, 1992.

Zoltai, T., and J. H. Stout. *Mineralogy, Concepts and Principles.* Minneapolis: Burgess Publishing Company, 1984.

Periodicals

Akasofu, S. I. “The Aurora: New Light on an Old Subject.” *Sky and Telescope* (December 1982): 534.

Arnold, L. “The Dynamic Aurora.” *Scientific American* (May 1989): 90.

Alverson K., F. Oldfield, and R. Bradley, eds. “Past Global Changes and Their Significance to the Future.” *Quaternary Science Reviews* 19, no. 1–5 (2000): 1–479.

“And Now, The Asteroid Forecast.” *Science* 285 (1999): 655.

Anderson, D. L. “Earth’s Viscosity.” *Science* 151 (1965): 321.

Arnold, L. “American Women in Geology, A Historical Perspective.” *Geology* 5 (1977): 493–4.

Arnold, L. “Florence Bascom and the Exclusion of Women from Earth Science Curriculum Materials.” *Journal of Geological Education* 23 (1975): 110–113.

“Assessing the Hazard: The Development of the Torino Scale.” *The Planetary Report* 19 (1999): 6–10.

Axelrod, D. I. “Fossil Floras Suggest Stable, Not Drifting Continents.” *Journal of Geophysical Research* 68 (1963): 3257.

Bard, E. “Ice Age Temperatures and Geochemistry.” *Science* 284 (May 1999): 1133–1134.

Bascom, W. “The Mohole.” *Scientific American* 200 (1959): 41–49.

Benin, A. L., J. D. Sargent, M. Dalton, and S. Roda. “High Concentrations of Heavy Metals in Neighborhoods Near Ore Smelters in Northern Mexico.” *Environmental Health Perspectives* 107, no. 4 (1999): 279–84.

Berger, A. L. “Milankovitch Theory and Climate.” *Reviews in Geophysics* no. 26 (1988): 624–657.

Blacket, P. M. S., E. C. Bullard, and S. K. Runcorn. “A Symposium on Continental Drift.” *Philosophical Transactions of the Royal Society* 1088 (1965): 145.

Blandford, R., and N. Gehrels. “Revisiting the Black Hole.” *Physics Today* (June 1999).

Bohr, N. “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” *Physical Review* (October 15, 1935): 696–702.

Bollen, M., S. Keppens, and W. Stalmans. “Specific Features of Glycogen Metabolism in the Liver.” In *Biochemistry Journal* 336 (1998): 19–31.

Bonatti, Enrico. “The Rifting of Continents.” *Scientific American* 256 (March 1987): 96–103.

Bowler, Sue. “Continent Turned Inside Out (Supercontinents Laurentia and Gondwanaland).” *New Scientist* 130 (June 15, 1991): 130.

Breed, C. S., S. G. Fryberger, S. Andrews, C. K. McCauley, F. Lennartz, D. Gebel, and K. Horstman. “Regional Studies of Sand Seas Using Landsat (ERTS) Imagery.” *A Study of Global Sand Seas*. Edited by E. D. McKee. U.S. Geological Survey Professional Paper 1052, 305–397.

Breslin, K. “Safer Sips: Removing Arsenic from Drinking Water.” *Environmental Health Perspectives* 106, 11, (1998): A 548–50.

Briden, J. C. “Palaemagnetic Polar Wandering.” *Palaeogeophysics* (1970): 277–289.

Browne, Malcolm W. “Physicists Create First Atoms of Antimatter.” *The New York Times,* (January 5, 1996): A1, A9.

Brunet, D., and D. A. Yuen. “Mantle Plumes Pinched in the Transition Zone.” *Earth and Planetary Science Letters* 178 (2000): 13–27.

Bullard, Sir Edward. “The Fit of the Continents Around the Atlantic.” *A Symposium on Continental Drift: Philosophical Transactions of the Royal Society of London* Series A 258, no. 1088 (October 1965): 41–51.

Burek C. V. “The First Lady Palaeontologist or Collector Par Excellence?” *Geology Today* 17, no. 5 (2001) 192–194.

Burek C. V. “Where are the Women in Geology?” *Geology Today* 17, no. 3 (2001) 110–114.

Bushman, J. R. “Uniformitarianism According to Hutton.” *Journal of Geological Education* 29 (January 1981): 31–33.

Cann, Rebecca L., Mark Stoneking, and Allan C. Wilson. “Mitochondrial DNA and Human Evolution.” *Nature* 325 (January 1987): 31–36.

Carey, S. W. “Continental Drift: A Symposium.” *Geology Department University of Tasmania: Hobert* (1958): 172–179.

Carozzi, A. V. “New Historical Data on the Origin of the Theory of Continental Drift.” *Geological Society of America Bulletin* 81 (1970): 283.

CLIMAP Project Members. “The Surface of the Ice-Age Earth.” *Science* 191 (March 1976): 1131–1137.

Collins, F. S., A. Patrinos, and E. Jordon, et al. “New Goals for the U.S. Human Genome Project.” *Science* 282 (October 23, 1998): 682–89.

“Computer Replicates Pangaea’s Breakup.” *Geotimes* 38 (March 1993): 9.

“Continental Plates Break Speed Limit.” *Geotimes* 38 (April 1993): 7.

Cox, A., and R. R. Doell. “Review of Paleomagnetism.” *Geological Society of America* Bulletin 71 (1960): 645.

Croswell, K. “The Best Black Hole in the Galaxy.” *Astronomy* (March 1992).

Dalziel, Ian. “Earth Before Pangaea.” *Scientific American* 272 (January 1995): 58–63.

Dalziel, Ian. “Paleozoic Laurentia-Gondwana Interaction and the Origin of the Appalachian-Andean Mountain System.” *Geological Society of America Bulletin* 106 (February 1994): 243–52.

Dalziel, Ian. “Appalachians and Andes Once Met.” *USA Today* 122 (1994): 12–13.

Dewey, J. F. “Plate Tectonics and Geosynclines.” *Tectonophysics* 10, nos. 5–6 (1970): 625–638.

Diamond, Jared. “Spacious Skies and Tilted Axes: Why Were Plants Domesticated So Early in the Fertile Crescent? And Why Did Those Crops then Spread So Far and So Fast?” *Natural History* 103 (1994): 16.

Dicke, R. H. “Average Acceleration of the Earth’s Rotation and the Viscosity of the Deep Mantle.” *Journal of Geophysical Research* 74 (1969): 5895.

Dickinson, W. R. “Plate Tectonic Models of Geosynclines.” *Earth and Planetary Science Letters* 10, no. 2 (1971): 165–174.

Dietz, Robert S., and John C. Holden. “The Breakup of Pangaea.” *Scientific American* (October 1970).

Einstein, A., B. Podolsky, and N. Rosen. “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” *Physical Review* (May 15, 1935): 777–780.

Elsasser, W. M. “Sea-Floor Spreading as Thermal Convection.” *Journal Geophysical Research* 76 (1971): 1101–1112.

Eubanks, M. W. “Hormones and Health.” *Environmental Health Perscpectives* 105, no. 5 (1997): 482–87.

Feder, Toni. “CERN Council Decides to Build LHC Now—and Pay for It Later.” *Physics Today* (February 1997): 58–59.

Fisher, Robert L., and Roger Revelle. “The Trenches of the Pacific.” *Continents Adrift* Scientific American.

Frankel, Henry. “From Continental Drift to Plate Tectonics.” *Nature* 335 (September 8, 1988): 127.

Galloway, Devin, David R. Jones, and S. E. Ingebritsen, eds. “Land Subsidence in the United States.” *U.S. Geological Survey Circular* 1182 (1999).

Goodacre, Alan. “Continental Drift.” *Nature* 354 (November 28, 1991): 261.

Gould, S. J., “Is Uniformitarianism Necessary?” *American Journal of Science* 263 (March 1965): 223–228.

Grieve, R. A. F. “Impact Cratering on the Earth.” *Scientific American* 262 (1990): 66–73.

Grollimund, B., and M. D. Zoback, “Did Deglaciation Trigger Intraplate Seismicity in the New Madrid Seismic Zone?” *Geology* 29, no. 2 (February 2001): 175–178.

Hamilton, W., and D. Krinsley. “Upper Palozoic Glacial Deposits of South Africa and South Australia.” *Geological Society of America Bulletin* 78 (1967): 783.

Haneberg, William C. “Determistic and Probabilistic Approaches to Geologic Hazard Assessment.” *Environmental & Engineering Geoscience* 6, no. 3 (August 2000): 209–226.

Haneberg, William C. “Drape Folding of Compressible Elastic Layers—II. Matrix Solution for Two-Layer Folds.” *Journal of Structural Geology* 15 (1993): 923–932.

Haneberg, William C. “Drape Folding of Compressible Elastic Layers–I. Analytical Solutions for Vertical Uplift.” *Journal of Structural Geology* 14 (1992): 713–721.

Hart, P. J., ed. “The Earth’s Crust and Upper Mantle.” *American Geophysical Union Geophysical Monograph* 13 (1969).

Hays, J. D., and N. D. Opdyke. “Antarctic Radiolaria, Magnetic Reversals and Climate Changes.” *Science* 158 (November 1967): 1001.

Heirtzler, J. R. “Marine Magnetic Anomalies Geomagnetic Field Reversals and Motions of the Ocean Floor Continents.” *Journal of Geophysical Research* 73 (1968).

Heirtzler, J. R. “Sea-Floor Spreading.” Biographical Notes and Bibliographies, *Scientific American* (1973).

Henbest, Nigel. “Continental Drift: The Final Proof.” *New Scientist* 102 (May 1984): 6.

Hess, H. H. “Gravity Anomalies in Island Structure.” *Proceedings of the American Philosophical Society* 79 (April 1938): 71–96.

Hilborn, R. C., and N. B. Tufillaro. “Nonlinear Dynamics.” *American Journal of Physics* 65, no. 822 (1997).

Hill, R. I., I. H. Campbell, and R. W. Griffiths. “Plume Tectonics and the Development of Stable Continental Crust.” *Exploration Geophysics* 22 (1991): 185–188.

Holden C. “Euro-women in Science.” *Science* 295, no. 5552 (2002): 41.

Holmes, A. “The Construction of a Geological Time-Scale.” *Transactions of the Geological Society of Glasgow* 21 (1947): 117–152.

Holmes, A. “A Revised Geological Time Scale.” *Transactions of the Edinburgh Geological Society* 17 (1959): 183.

Hooke, Roger L. “On the History of Humans as Geomorphic Agents.” *Geology* 28, no. 9 (September 2000): 843–846.

Horgan, John. “Profile: Reluctant Revolutionary: Thomas S. Kuhn Unleashed Paradigm on the World.” *Scientific American* 264 (May 1991): 40.

Hospers, J., and S. I. Van Andel. “Paleomagnetic Data from Europe and North America and Their Bearing on the Origin of the North Atlantic Ocean.” *Tectonophysics* 6 (1968): 475.

Hubbert, M. King. “Darcy’s Law: Its Physical Theory and Application to the Entrapment of Oil and Gas.” *History of Geophysics* 3 (1987): 1–27.

Hubbert, M. King. “The Theory of Ground-Water Motion.” *Journal of Geology* 48 (1940): 785–944.

Hudson, Richard L. “Supercollider’s Post-mortem Costs May Mount.” *The Wall Street Journal* (26 November 1993): B1, B9.

Hurley, P. M. “Test of Continental Drift by Comparison of Radiometric Ages.” *Science* 157 (1967): 495.

——— “The Confirmation of Continental Drift.” *Scientific American* 218, no. 4 (1968): 53.

Hurley, P. M., and J. R. Rand. “Predrift Continental Nuclei.” *Science* 164 (June 1969): 1229.

Hynes, Andrew. “Two-Stage Rifting of Pangaea by Two Different Mechanisms.” *Geology* 18 (April 1990): 323–6.

Isacks, Bryan L. “Andean Tectonics Related to Geometry of Subducted Nazca Plate.” *Geological Society of America Bulletin* 94 (July 1984): 341–61.

Isacks, Bryan L. “Seismology and the New Global Tectonics.” *Journal of Geophysical Research* 73 (1968): 5855.

Iverson, Richard M. “The Physics of Debris Flows.” *Reviews of Geophysics* 35, no. 3 (August 1997): 245–296.

Jacobs, J. A. “The Earth’s Magnetic Field.” *Contemporary Physics* 36 (July 1995): 267–77.

——— “Reversals of Earth’s Magnetic Field.” *Geological Magazine* 132 (September, 1995): 625–6.

Johnston, Arch C., and B. Schweig. “The Enigma of The New Madrid Earthquakes of 1811–1812.” *Annual Review of Earth and Planetary Sciences* 24: (1996): 339–84.

Jordan, Thomas H. “The Deep Structure of the Continents.” *Scientific American* (January 1979): 70–82.

Jordan, Thomas H. “A Procedure for Estimating Lateral Variations from Low-Frequency Eigen Spectra Data.” *Geophysical Journal of Research* 52 (1978): 441–445.

Kennedy, G. C., and B. E. Nordie. “The Genesis of Diamond Deposits.” *Economic Geology* 63 (1996): 495–503.

Kerr, Richard A. “Continental Drift Nearing Certain Detection (Very Long Baseline Interferometry).” *Science* 229 (1985): 953–5.

Kerr, Richard A. “How Far Did the West Wander?” *Science* 268 (May 5, 1995): 635–7.

Koban, C. G., and G. Schweigert. *Facies* 29 (1993): 251–264.

LePichon, X. “Sea-Floor Spreading and Continental Drift.” *Journal of Geophysical Research* 73, no. 12 (June 1968): 3661.

Lewin, Roger. “Genes From a Disappearing World (Human Genome Diversity Project).” *New Scientist* 138 (1993): 25–29.

Manuel, J. “NIEHS and CDC Track Human Exposure to Endocrine Disruptors.” *Environmental Health Perspectives* 107, no. 1 (1999): A16.

Matthews, Drummond H., and Simon L. Klemperer. “Deep Sea Seismic Reflection Profiling.” *Geology* 15 (March 1997): 195–8.

Maxwell, J. C. “Continental Drift and a Dynamic Earth.” *American Science* 56 (1968): 35.

McKenzie, D. P. “Speculations on the Consequences and Causes of Plate Motions.” *Geophysical Journal of Research* 18 (1969): 1–32.

McKenzie, D. P., and R. L. Parker. “The North Pacific: An Example of Tectonics on a Sphere.” *Nature* 216 (1967): 1276–1280.

McKenzie, D. P., and N. O. Weiss. “Speculations on Thermal and Tectonic History of the Earth.” *Geophysical Journal of Research* 42 (1975): 131–174.

McKenzie, D. P., R. L. Fisher, and J. G. Sclater. “Evolution of the Central Indian Ridge, Western Indian Ocean.” *Bulletin of the Geological Society of America* 82 (March 1971): 553–562.

McPhee, John A. “Assembling California.” *New Yorker* 8 (September 21, 1992): 39–49.

Meinzer, O. “Outline of Ground-Water Hydrology with Definitions.” *U.S. Geological Survey Water-Supply Paper* 577, 1923.

Melosh, H. Jay. “The Mechanics of Large Rock Avalanches.” *Debris Flows/Avalanches: Process, Recognition, and Mitigation. Geological Society of America Reviews in Engineering Geology* 7 (1987): 41–49.

Menard, H. W. “Sea Floor Spreading, Topography, and the Second Layer.” *Transactions American Geophysical Union* 48, no. 1 (March 1967): 217.

Meyerhoff, A. A. “Continental Drift: Implications of Paleomagnetic Studies and Physical Oceanography.” *Journal of Geology* 78 (1970): 1.

Monastersky, Richard. “Spinning Supercontinent Cycle.” *Science News* 135 (June 1989): 344.

Monroe, C., D. M. Meekhof, B. E. King, and D. J. Wineland. “A ‘Schrodinger Cat’ Superposition State of an Atom.” *Science* 272 (May 24, 1996).

Moores, E. M. “Ultramatics and Orogeny, with Models of the US Cordillera and the Tethys.” *Nature* 228 (1970): 837–842.

Morgan, W. J. “Convection Plumes in the Lower Mantle.” *Nature* 230 (March 5, 1971): 42.

Morgan, W. J. “Rises, Trenches, Great Faults, and Crustal Blocks.” *Journal of Geophysical Research* 73 (1968): 1959.

Murphy, J. Brendan. “Mountain Belts and the Supercontinent Cycle.” *Scientific American* 266 (April 1992): 84–91.

“NASA Measures Continental Drift.” *Earth Sciences* 38 (1985): 8–9.

“NASA Tests Confirm Continental Drift.” *International Wildlife* 14 (September 1984): 31.

Nesje, A., and Ian M. Whillans. “Erosion of Sognefjord, Norway.” *Geomorphology* no. 9 (1994): 33–45.

Newhall, Christopher G., and Daniel Dzurisin, “Historical Unrest at Large Calderas of the World.” *U.S. Geological Survey Bulletin 1855* (1988).

Nobumichi, S. “Analyzing Rocks with Microbeams.” *Oceanus* 38, no. 1 (1995): 28–29.

“Ocean Drilling Program: Breakup of Gondwanaland.” *Nature* 337 (January 19, 1989): 209–10.

Oliver, Jack E. “The Big Squeeze: How Plate Tectonics Redistributes Mineral and Organic Resources.” *The Sciences* 31 (July 1991): 22–28.

Opening of the Caribbean." *Oceanus* 30 (Winter 1987): 49–50.

Orowan, E. "Continental Drift and the Origin of Mountains." *Science* 146 (1964): 1003.

Orowan, E. "The Origin of the Oceanic Ridges." *Scientific American* 221, no. 5 (November 1969): 102–118.

Parker, Robert L. "The Determination of Seamount Magnetism." *Geophysical Journal of Royal Astronomical Society* 24 (1971): 321–324.

Petford, N., et al. "Granite Magma Formation, Transport and Emplacement in the Earth's Crust." *Nature* (December 2000): 669–673.

Phillips, J. D. "Plate Tectonics, Paleomagnetism and the Opening of the Atlantic." *Bulletin of the Geological Society of America* 82 (1972): 1579.

Plant J. A., D. Hackett, and B. J. Taylor. "The Role of Women in the British Geological Survey." *Geology Today* 10, no. 4 (1994): 151–156.

Raff, A. D., and R. G. Mason. "Magnetic Survey of the West Coast of North America." *Bulletin of the Geological Society of America* 72 (1961): 1267–1270.

Reid, M. E., et al. "Gravitational Stability of Three-Dimensional Stratovolcano Edifices." *Journal of Geophysical Research* 105, B3 (March 2000): 6043–6056.

"Reversals of the Earth's Magnetic Field." *Philosophical Transactions of the Royal Society of London: Series A, Mathematical and Physical Sciences* 263, no. 1143 (December 1968): 481–524.

Romm, James. "A New Forerunner for Continental Drift (Abraham Ortelius) Suggested the Basic Elements of the Continental Drift Theory in 1596." *Nature* 367 (February 1994): 407–8.

Runcorn, S. K. "Continental Drift." *Scientific American* 208 (1963): 86.

Sager, W., and Koppers, A. "Late Cretaceous Polar Wander of the Pacific Plate: Evidence of a Rapid True Polar Wander." *Science* 287 (January 2000): 455–459.

Sarjeant, W. A. S. "Alice Wilson, First Woman Geologist with the Geological Survey of Canada." *Earth Sciences History* 12, no. 2 (1993): 122–128.

"Scaling the Degree of Danger from an Asteroid." *Nature* 400 (1999): 392.

Shen, Zheng-Kang, et al. "Crustal Deformation Across and Beyond the Los Angeles Basin From Geodetic Measurements." *Journal of Geophysical Research* 101 (1996): 27, 957–27, 980.

Shopov, Y. Y. "Genetic Classification of Cave Minerals." *Proceedings of Tenth International Congress of Speleology* 1 (1989): 101–105.

Shopov, Y. Y. "Speleothem Records of Environmental Changes in the Past." *Contribucion del Estudio Cientifico De Las Cavidades Karsticas Al Conocimiento Geologico* Instituto de Investigacion, 1999: 117–134.

"SHRIMP Instrument Homes in on Solar System Mysteries." *Electronic Design* 47, no. 3 (February 8, 1999): 23.

Sloss, L. L. "Paleoclimatic and Tectonic Control on the Accumulation of North American Cratonic Sediment." *Bulletin of the Geological Society of America* 107 (September 1995): 1123–1126.

Smith, A. G. "The Fit of the Southern Continents." *Nature* 225 (1970): 139.

Spotts, Peter N. "Antimatter Happens, in European Lab." *Christian Science Monitor* (January 8, 1996): 4.

Stehli, F. G., and C. E. Helsley. "Paleontologic Technique for Defining Ancient Pole Positions." *Science 142* (November 1963): 1057.

Stewart, J. "Basin and Range Structure—A System of Horsts and Grabens Produced by Deep-Seated Extension." *Bulletin of the Geological Society of America* 82, no. 4 (April 1971): 1019–1043.

Stoffler, D., and R. A. F. Grieve. "Classification and Nomenclature of Impact Metamorphic Rocks." *Lunar and Planetary Science* 25 (1994): 1347–1348.

Story, Michael, John Mahoney, and A. D Saunders. "Timing of Hot Spot-related Volcanism and the Breakup of Madagascar and India." *Science* 267 (1995): 852.

Svitil, K. "Probing the Past." *Discover* 19, no. 11 (November 1998): 96–99.

Sykes, Lynn R., and Steven C. Jaume. "Changes in State of Stress on the Southern San Andreas Fault Resulting from the California Earthquake Sequence of April to June 1992." *Science* 258 (November 1992): 1325–1328.

Sykes, Lynn R., and Leonardo Seeber. "Great Earthquakes and Great Asperities, San Andreas Fault, Southern California." *Geology* 13 (December 1985): 835–838.

Taubes, Gary. "Schizophrenic Atom Doubles as Schrodinger's Cat or Kitten." *Science* 272, no. 5265 (May 24, 1996).

"The Torino Impact Hazard Scale." *Planetary and Space Science* 48 (2000): 297–303.

"The Torino Scale: Gauging the Impact Threat." *Sky & Telescope* 98 (1999): 32–33.

Torrens, H., et al. "Etheldred Benett or Wiltshire, England, the First Lady Geologist—Her Fossil Collection in the Academy of Natural Science of Philadelphia and the Rediscovery of 'Lost' Specimens of Jurassic Trigonlidae With Their Soft Anatomy Preserved." *Proceedings of the Academy of Natural Sciences of Philadelphia* 150 (2000): 59–123.

Turco, R. P., A. B. Toon, T. P. Ackerman, J. B. Pollack, and C. Sagan. “Nuclear Winter: Global Consequences of Multiple Nuclear Explosions.” *Science* no. 222 (1983): 1283–1297.

Valentine, James W. “Late Precambrian Bilaterians: Grades and Clades.” *Proceedings of the National Academy of Sciences of the United States of America* 91 (July 1994): 6751–6757.

Vine, F. J. “Spreading of the Ocean Floor: New Evidence.” *Science* 154, no. 3775 (December 1996): 1405–1515.

Von Herzen, R. P. “The Deep Sea Drilling in the South Atlantic.” *Science* 168 (May 1970): 1047–1059.

Wearner, R. “The Birth of Radio Astronomy.” *Astronomy* (June 1992).

Weijermars, Ruud. “Global Tectonics Since the Breakup of Pangea 180 Million Years Ago: Evolution Maps and Lithospheric Budget.” *Earth-Science Reviews* 26 (February 1989): 113–62.

Weisburd, Stefi. “Seeing Continents Drift (Very Long Baseline Interferometry and Satellite Laser Ranging).” *Science News* 128 (1985): 388.

Wieczorek, Gerald F., et al. “Unusual July 10, 1996, Rock Fall at Happy Isles, Yosemite National Park, California.” *Bulletin of the Geological Society of America* 112, no. 1 (January 2000): 75–85.

Wilkes, B. “The Emerging Picture of Quasars.” *Astronomy* (December 1991).

Willett, Sean D., and Christopher Beaumont. “The India-Asia Collision: What Gives?” *Science News* 146 (1994): 15.

Wilson, I. “Desert Sandflow Basins and a Model for the Development of Ergs.” *Geographical Journal* 137, no. 2 (1971): 180–199.

Wilson, J. T. “A New Class of Faults and Their Bearing on Continental Drift.” *Nature* 207 (1965): 343.

Wilson, Jim. “Executing Schrodinger’s Cat.” *Popular Mechanics* 174, no. 10.

Wright, and Pierson. “Living With Volcanoes.” *The U.S. Geological Survey’s Volcano Hazards Program* U.S. Geological Survey Circular (1973).

Wysession, Michael. “The Inner Workings of the Earth.” *American Scientist* 83 (1995): 134.

Yakiko, Tanaka, et al. “Compilation of Thermal Gradient Data in Japan on the Basis of the Temperatures in Boreholes.” *Bulletin Of The Geological Survey Of Japan* 50, no. 7 (1999): 457–487.

York, Derek. “The Earliest History of the Earth.” *Scientific American* 268 (January 1993): 90–96.

Internet Sites

Editor’s Note: As the World Wide Web is constantly expanding, the URLs listed below were current as of May 11, 2002.

Allison, Henry E. “Immanuel Kant.” [cited August 21, 2000]. <http://www.columbia.edu/~pjs38/biokant.htm>.

American Meteorological Society. “Challenges of Our Changing Atmosphere—Careers in Atmospheric Research and Applied Meteorology.” 1993 [cited March 1, 2002]. <http://www.ametsoc.org/AMS/pubs/careers.htm>.

American Physical Society. “Henry Augustus Rowland (1848–1901).” 1998 [cited August 21, 2002]. <http://www.aps.org/apsnews/1198/119806.htm>.

Ball, Philip. “Move Any Mountain.” September 22, 2000 [cited February 26, 2002]. <http://www.nature.com/nsu/000928/000928-1.htm>.

Beebe, William. “Half Mile Down.” 1934 [cited May 2, 2002]. <http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/htm>/ocean_planet_book_beebe1.htm>.

Brock, Henry M. Transcribed by Dennis McCarthy. (Copyright: Kevin Knight.) “Gaspard-Gustave de Coriolis.” *The Catholic Encyclopedia.* 1999 [cited August 21, 2000]. <http://www.newadvent.org/cathen/04370a.htm>.

Brooklyn College City University of New York. “Dinosaur Core.” Chamberlain, John A. Jr., Dept. of Geology. [cited May 10, 2002]. <http://academic.brooklyn.cuny.edu/geology/chamber/gesner.htm>.

Brown, Kevin. “The Path to Mass-Energy Equivalence.” [cited August 2000]. <http://mathpages.com/home/albro/albro8.htm>.

Camp, V. Department of Geological Sciences, San Diego State University and NASA. “How Volcanoes Work.” 2000 [cited March 21, 2002]. <http://www.geology.sdsu.edu/how_volcanoes_work/.htm>.

Canadian Center for Remote Sensing. “History of Remote Sensing.” 2000 [cited May 10, 2002]. <http://www.ccrs.nrcan.gc.ca/ccrs/org/history/morleye.htm>.

Canadian Center for Remote Sensing. “Radarsat Technical Specs—Summary.” 2000 [cited January 2002]. <http://www.Ccrs.nrcan.gc.ca/ccrs/radspece.htm>.

Carver, G., and O. Garrett, Centre for Atmospheric Science, University of Cambridge. “The Ozone Hole Tour.” 1999 [cited April 22, 2002]. <http://www.atm.ch.cam.ac.uk/tour/.htm>.

Centre for Marine Environmental Sciences (MARUM). “World Data Center for Marine Environmental Sciences.” 2001 [cited December 17, 2000]. <http://www.pangaea.de/wdc-mare/.htm>.

Clyde, John, Johann Schleier-Smith, and Greg Tseng. “Equivalence of Mass and Energy.” *Nuclear Physics: Past, Present, and Future.* October 1996 [cited August 21, 2002].

<http://library.thinkquest.org/3471/energy_mass_equivalence.htm>.

Dana, P. The Geographer's Craft Project, Department of Geography, University of Colorado at Boulder. "Map Projection Overview." 1999 [cited October 3, 2000]. <http//www.colorado.edu/geography/gcraft/notes/mapproj/mapproj.htm>.

Daniels, Alison. (Copyright: The University of Edinburgh.) "Point of Creation: The Higgs Boson." 2000 [cited August 21, 2000]. <http://www.cpa.ed.ac.uk/edit/07/articles/03.htm>.

Environmental Protection Agency, Office of Water. 2002 [cited May 11, 2002]. <http://www.epa.gov/owow/estuaries/about1.htm>.

EPA. Gulf of Mexico Program. "The Gulf of Mexico Watershed." 2002 [cited March 31, 2002]. <http://www.epa.gov/gmpo/edresources/watrshed.htm>.

Fischer, R. V. "The Volcano Information Center." University of California at Santa Barbara, Department of Geological Sciences. 1999 [cited March 24, 2002]. <http://www.geol.ucsb.edu/~fisher/.htm>.

Florida State University, Department of Meteorology. "Meteorology—A Brief History." [cited March 1, 2002]. <http://www.met.fsu.edu/explores/methist.htm>.

Fowler, Michael. "Tycho Brahe." 1995 [cited August 21, 2000]. <http://www.phys.virginia.edu/classes/109N/1995/lectures/tychob.htm>.

Galileo Project at Rice University. Van Helden, Albert. "Catalog of the Scientific Community: Agricola, Georgius (Georg Bauer)." Compiled by Richard S. Westfall, Indiana University. 1995 [cited May 11, 2002]. <http://es.rice.edu/ES/humsoc/Galileo/Catalog/Files/agricola.htm>.

Geography Exchange. 2002 [cited May 11, 2002]. <http://www.zephryus.demon.co.uk/geography/resources/glaciers/arete.htm>.

Geophysical Institute, University of Alaska Fairbanks. "Continental Divide, Alaska Science Forum." [cited January 31, 2002]. <http://www.gi.alaska.edu/ScienceForum/ASF0/023.htm>.

Glenn Brown. "Darcy's Law Basics and More." Oklahoma State University. [cited May 11, 2002]. <http://biosytems.okstate.edu/darcy/LaLoi/index.htm>.

Hamilton, Calvin J. "Neptune." 1997–2000 [cited August 21, 2000]. <http://planetscapes/com/solar/eng/neptune.htm>.

Hartwick College, Department of Geological and Environmental Sciences. "The Pleistocene Ice Age." 2001 [cited January 20, 2002]. <http://www.hartwick.edu/geology/work/VFT-so-far/glaciers/glacier1.htm>.

Hines, C. "The Official William Beebe Web Site." 2000 [cited May 3, 2002]. <http://hometown.aol.com/chines6930/mw1/beebe1.htm>.

Hulse, Russell Alan. The Nobel Foundation. "Autobiography of R. A. Hulse." 1993 [cited August 21, 2000]. <http://www.nobel.se/physics/laureates/1993/hulse/autobio.htm>.

Illinois State Museum. "Ice Ages." 2002 [cited January 25, 2002]. <http://www.museum.state.il.us/exhibits/ice_ages/why_glaciations1.htm>.

International Council for Science. "International Council for Science." 1996 [cited December 17, 2000]. <http://www.icsu.org>.

Kanen, Rob. "The Emplacement and Origin of Granite." 2001 [cited May 11, 2002]. <http://www.geologyone.com/granite1.htm>.

Kious, W. J., and R. I. Tilling, "This Dynamic Earth, the Story of Plate Tectonics." Online Version 1.08, United States Geological Survey. 2001 [cited May 10, 2002]. <http://pubs.usgs.gov/publications/text/dynamic.htm>.

Kraan-Korteweg, Renée C., and Ofer Lahav. "Galaxies Behind the Milky Way." *Scientific American.* 2000 [cited August 21, 2000]. <http://www.sciam.com/1998/1098issue/1098laham.htm>.

Liss, Tony, and P. L. Tipton. "The Discovery of the Top Quark." 1997 [cited August 21, 2000]. <http://www.sciam.com/0997issue/0997tipton.htm>.

Maine Department of Conservation, Maine Geological Survey. Bald Mountain, Washington Plantation, Maine. 2001 [cited March 2001]. <http://www.state.me.us/doc/nrimc/mgs/sites-2001/mar01.htm>.

Met Office. "Interpreting Weather Maps." [cited March 1, 2002]. <http://www.met-office.gov.uk/education/curriculum/leaflets/weathermaps.htm>.

NASA, Ocean Color, Data and Resources. "Classic CZCS Scenes Chapter 6: Gulf Stream Rings." 1999 [cited March 31, 2002]. <http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/OCDST/classic_scenes/07_classics_rings.htm>.

NASA's Observatoriuum. "Hydrologic Cycle." 1995-1999 TRW, Inc. [cited January 9, 2002]. <http://observe.ivv.nasa.gov/nasa/earth/hydrocycle/hydro1.htm>.

National Drought Mitigation Center. "Understanding and Defining Drought." 1995 [cited January 9, 2002]. <http://www.ndmc.gov>.

National Geophysical Data Center. "The World Data Center System." 2000 [cited December 17, 2000]. <http://www.ngdc.noaa.gov>.

National Oceanic and Atmospheric Administration. "Paleoclimatology Program, Glaciation." 1999 [cited January 20, 2002]. <http://www.ngdc.noaa.gov/paleo/glaciation.htm>.

National Oceanographic and Atmospheric Administration. “Coral Reefs.” 2002 [cited May 11, 2002]. <http://www.noaanews.noaa.gov/magazine/stories/mag7.htm>.

National Weather Service. “East Central Florida Rip Current Program.” 1999 [cited January 21, 2002]. <http://www.srh.noaa.gov/mlb/ripinit.htm>.

Naval Meteorology and Oceanography Command. “The Restless Sea.” [cited January 21, 2002]. <http://pao.cnmoc.navy.mil/pao/Educate/OceanTalk2/indexrestless.htm>.

New Mexico Bureau of Geology and Mineral Resources. “Master Page.” 2000 [cited March 1, 2002]. <http://tremor.nmt.edu/pioneers/dlMoho_32.htm>.

Nobel Foundation. “Pieter Zeeman.” 2000 [cited August 21, 2000]. <http://www.nobel.se/physics/laureates/1902/zeeman-bio.htm>.

Nobel Foundation. “Wilhelm Conrad Röntgen.” 1999 [cited August 21, 2000]. <http://www.nobel.se/physics/laureates/1901/rontgen-bio.htm>.

NPA Group, Satellite Mapping and Exploration. “Ancient Landscapes, Information and Computers.” 2001 [cited April 22, 2002]. <http://www.npagroup.com/rs_intro/index.htm>.

“Nuclear Winter and Other Scenarios.” [cited January 31, 2002]. <http://www.pynthan.org/vri/nwaos.htm>.

“Nuclear Winter.” [cited January 31, 2002]. <http://zebu.uoregon.edu/~js/glossary/nuclear_winter.htm>.

O’Connor, J. J., and E. F. Robertson. “Jean Baptiste Josephe Fourier.” 1997 [cited August 21, 2000]. <http://www-history.mcs.st-and.ac.uk/history/Mathematicians/Fourier.htm>.

O’Connor, J. J., and E. F. Robertson. “Leonardo da Vinci.” 1996 [cited August 21, 2000]. <http://turnbull.dcs.st-and.ac.uk/history/Mathematicians/Leonardo.htm>.

Oak Ridge National Laboratory. “The Obsidian Clock.” [cited April 16, 2002]. <http://www.ornl.gov/reporter/no7/clock.htm>.

Ohio State University. “Wastewater Treatment Principles and Regulations.” 1996 [cited February 27, 2002]. <http://ohioline.osu.edu/aex-fact/0768.htm>.

Okanagan University College, Geography Department. “Introduction to Geomorphology: Glaciation.” 2001 [cited January 25, 2002]. <http://www.geog.ouc.bc.ca/physgeog/contents/11n.htm>.

PaleoZoo, the Geobobological Society. 1998 [cited March 20, 2001]. <http//www.geobop.com/paleozoo>.

PBS Online. “William Beebe: Going Deeper.” 1999 [cited May 3, 2002]. <http://www.pbs.org/wgbh/amex/ice/sfeature/beebe.htm>.

PBS.org. “The Deep Sea—Journey to the Ocean Floor.” [cited February 15, 2002]. <http://www.pbs.org/wnet/savageseas/deep-side-journey.htm>.

Physics & Astronomy Department, George Mason University. “The Cosmos From The Earth.” [cited November 24, 1998]. <http://www.physics.gmu.edu/classinfo/astr103/CourseNotes/ECText/ch01_txt.htm>.

Pidwirny, M. J. Department of Geography, Okanagan University College. “Fundamentals of Physical Geography.” 2001 [cited March 17, 2002]. <http//www.geog.ouc.ca/physgeog/contents/la.htm>.

Pickford, Ron. “The Father of English Geology.” [cited May 11, 2002]. <http://www.bath.ac.uk/BRLSI/wsmith.htm>.

Raymond, L.A. “Petrology: The Study of Igneous, Sedimentary, and Metamorphic Rocks.” 1995 [cited May 11, 2002]. <http://geology.csupomona.edu/drjessey/class/GSC425/Ig-Met25.htm>.

Regents of the University of Michigan. “Biographical Information for Martinus J. G. Veltman.” 1998 [cited August 21, 2000]. <http://www.physics.lsa.umich.edu/veltmanbiographical.htm>.

Rice University, Department of Earth Science. “Ice.” 1997 [cited January 25, 2002]. <http://www.glacier.rice.edu/>.

Royal Danish Embassy. “H. C. Ørsted.” 1998 [cited August 21, 2000]. <http://www.denmarkemb.org/oersted.htm>.

Schewe, Phillip, and Ben Stein. “Physics News Update: The 1999 Nobel Prize for Physics.” 1999 [cited August 21, 2000]. <http://www.physics.uq.edu.au/media/Nobel99.htm>.

School of Mathematics and Statistics, University of St. Andrews, Scotland. “Simon Stevin,” by O’Connor, J. J., and E. F. Robertson. December 1996 [cited May 11, 2002]. <http//www-history.mcs.st-andrews.ac.uk/history/References/Stevin.htm>.

Sea, Grant. “Rip Currents: Don’t Panic.” [cited January 21, 2002]. <http://www.ncsu.edu/seagrant/PDF/RipBrochure.pdf>.

“Solar Eclipse Journal,” 1999-2002 [cited April 24, 2002]. <http//www.designbg.com/sej>.

Spergel, David N., Gary Hinshaw, and Charles L. Bennett. “The Milky Way.” *Microwave Anisotropy Probe.* May 1, 2000 [cited August 21, 2000]. <http://map.gsfc.nasa.gov/htm>/milky_way.htm>.

Stoner, Ron. “Relativistic Dynamics.” April 3, 1999 [cited August 21, 2000]. <http://fermi.bgsu.edu/~stoner/P202/relative2/sld001.htm>.

Strange Science. “Rocky Road: Abraham Gottlob Werner,” by Michon Scott. [cited May 11, 2002]. <http://turnpike.net/~mscott/werner.htm>.

The U.S. Global Change Research Information Office. "Dust Storm Magnitude, Duration and Frequency." [cited March 1, 2002]. <http://www.gcrio.org/geo/dust.htm>.

Thomas, Dan. "Jean-Baptiste Joseph Fourier." 1996 [cited August 21, 2000]. <http://www.chembio.uoguelph.ca/educmat/chm386/rudiment/tourclas/fourier.htm>.

Tilling, R. I. "Volcanoes, On-line Edition." United States Geological Survey. 1997 [cited March 24, 2002]. <http://pubs.usgs.gov/gip/volc>.

Topinka, Lyn. "Mount St. Helens: A General Slide Set." October 18, 2001 [cited March 11, 2002]. <http://vulcan.wr.usgs.gov/Photo/SlideSet/ljt_slideset_old.htm>.

United States Environmental Protection Agency Web Site. 2002 [cited April 19, 2002]. <http://www.epa.gov>.

United States Geological Survey. "CVO Website—Hazards—Lahars." 2000 [cited February 15, 2002]. <http://vucan.wr.usgs.gov/Hazards/NRC_Definitions/lahars.htm>.

United States Geologic Survey, Volcano Hazards Program. "Photo Glossary of Volcano Terms." 2002 [cited March 24, 2002] <http://volcanoes.usgs.gov/Products/Pglossary/pglossary.htm>.

United States Geological Survey National Earthquake Information Center. "Andrija Mohorovicic." 2001 [cited March 1, 2002]. <http://neic.usgs.gov/neis/seismology/people/mohorovicic.htm>.

United States Geological Survey. "USGS Minerals Information." January 30, 2002 [cited April 22, 2002]. <http://minerals.usgs.gov>.

United States Geological Survey. "USGS Photo Glossary." November 16, 2001 [cited April 10, 2002]. <http://volcanoes.usgs.gov/Products/Pglossary/.htm>.

United States Geological Survey. "This Dynamic Earth." [cited August 2001]. <http://pubs.usgs.gov/publications/text/dynamic.htm>.

United States Lifeguards for Life, "Rip Currents—Rivers Through The Surf." [cited January 21, 2002]. <http://www.usla.org/PublicInfo/beach_safety/rip_current1.shtm>.

U.S. Naval Observatory, Astronomical Applications Department. "The Seasons and the Earth's Orbit—Milankovitch Cycles." [cited April 27, 2002]. <http://aa.usno.navy.mil/>.

University of California, Berkeley. "Museum of Paleontology, Geology Wing." 1994–2000 [cited May 11, 2002]. <http://www.ucmp.berkeley.edu/exhibit/geology.html>.

University of California at Berkeley. "William Smith." [cited May 11, 2002]. <http://www.ucmp.berkeley.edu/history/smith.htm>.

University of Cambridge. "Our Own Galaxy: The Milky Way." *Cambridge Cosmology* May 16, 2000 [cited August 21, 2000]. <http://www.damtp.cam.ac.uk/user/gr/public/gal_milky.htm>.

University of Delaware "Extreme 2000: Voyage to the Deep, A Brief History." 2000 [cited February 15, 2002]. <http://www.ocean.udel.edu/deepsea/level-2/tools/history.htm>.

University of East Anglia, Norwich, School of Information Systems. "Satellite Imagery and GIS." 2000 [cited April 22, 2002]. <http://www.sys.uea.ac.uk/Research/researchareas/JWMP/Default.htm>.

University of Notre Dame Archives. "Lating Dictionary and Grammar Aid." Maintained by William Kevin Cawley. University of Notre Dame. [cited December 21, 2001]. <http://www.nd.edu/~archives/latgramm.htm>.

University of Wisconsin—Stevens Point Virtual Geography. 2002 [cited May 11, 2002]. <http://www.uwsp.edu/geo/projects/virtdept/ipvft/arete.htm>.

University of Wisconsin-Madison. "Weather for Pilots." 2000 [cited March 27, 2002]. <http://itg1.meteor.wisc.edu>.

Van Helden, Albert. "Tycho Brahe." 1995 [cited August 21, 2000]. <http://es.rice.edu/ES/humsoc/Galileo/People/tycho_brahe.htm>.

Watson, K. United States Geological Survey. "Volcanoes: Principle Types of Volcanoes." 1997 [cited March 18, 2002]. <http://pubs.usgs.gov/gip/volc/types.htm>.

Wellesley University. "Annie Jump Cannon: Understanding Her Work." 1998 [cited December 21, 1998]. <http://www.wellesley.edu/Astronomy/annie/understanding.htm>.

"When the Earth Moves—Of Magnetism and Time." The National Academies. [cited May 11, 2002]. <http://www4.national-academies.org/beyond/beyonddicovery.nsf/web/seafloor5?OpenDocument.htm>.

Wills, Jamal. "Coriolis Effect." *Living Universe Foundation.* 1996 [cited August 21, 2000]. <http://www.luf.org/bin/view/GIG/CoriolisEffect-CoriolisForceTerm.htm>.

York University, Department of Geography. "Glacial Processes." 1996 [cited January 20, 2002]. <http://www.yorku.ca/faculty/academic/arobert/14008.htm>.

HISTORICAL CHRONOLOGY

Editor's note: This is a historical chronology principally devoted to marking milestones in human scientific achievement or observation. Detailed information related to the eons, eras, periods, and epochs of geologic time may be found in text and diagrams related to the topic Geologic time.

c.4,600,000,000 B.C.
Origin of Earth: 4,600 million years ago (mya).

c.4,000,000 B.C.
Earliest hominid species appear on Earth.

c.50,000 B.C.
Homo sapiens sapiens emerges as a conscious observer of nature.

c.30,000 B.C.
Stone Age cultures use pigments to color various artifacts.

c.10,000 B.C.
Neolithic Revolution: transition from a hunting and gathering mode of food production to farming and animal husbandry, that is, the domestication of plants and animals.

c.4000 B.C.
Early applied chemistry begins in Egypt with the extraction and working of metals, including copper, tin, and bronze. Egyptians are also familiar with eye paint and plaster of Paris.

c.4000 B.C.
Egyptians astronomically measure time.

c.3500 B.C.
Sumerians describe methods of managing the date harvest.

c.3400 B.C.
Bronze, an alloy of copper and tin, first appears in abundance in Samaria. The Sumerians become expert in working gold, silver, copper, lead, and antimony.

c.3000 B.C.
Iron is forged.

c.2500 B.C.
The earliest known wholly glass objects are beads made in Egypt at this time. Early peoples may have discovered natural glass, which is created when lightning strikes sand. The Egyptians make glass beads by sand (silica), soda, lime, and other ingredients.

c.2000 B.C.
Chinese document experiments with forces of magnetism.

c.1500 B.C.
Use of iron becomes prevalent in the Mediterranean. It appears to have come there from the northeast, possibly beginning with the Hittites, and its use revolutionizes society.

c.900 B.C.
Steel is manufactured in India.

c.700 B.C.
Babylonians and Chinese understand planetary orbits.

c.700 B.C.
Greeks demonstrate force of electric attraction produced by rubbing amber.

c.700 B.C.
The use of anatomical models is established in India.

c.600 B.C.
Anaximander, Greek astronomer, describes the ecliptic plane, and asserts that Earth's surface assumes a curved, cylindrical shape.

c.600 B.C.

Thales of Miletus, Greek philosopher, first notices the electrification of amber (the Greek word for amber is *elektron*) by friction. Thales also proposes water as the fundamental substance of the Universe. He is the first to systematically study magnetism, and correctly predicts a solar eclipse.

c.550 B.C.

Pythagoras, Greek philosopher and mathematician, advances studies of geometry and geometric form. Pythagoras asserts Earth as a sphere.

c.525 B.C.

Anaximenes, Greek philosopher, proposes that air is the fundamental element of the Universe, and when compressed, it can take the form of water and Earth.

c.500 B.C.

Heraclitus, Greek philosopher, states that fire is the fundamental element of the universe. He also states that all things are in constant motion and that nothing is ever lost.

c.500 B.C.

Parmenides, Greek philosopher, suggests that matter can be neither created nor destroyed.

c.480 B.C.

Oenopides of Chios calculates angle of Earth's polar axial tilt to ecliptic .

c.475 B.C.

Parmenides argues that Earth is a sphere.

c.460 B.C.

Eudoxus of Cnidus, Greek philosopher, corrects faults in Plato's planetary orbital scheme (e.g., that Sun, planets, and stars orbit Earth on celestial spheres).

c.455 B.C.

Philolaus, Greek philosopher, argues that night and day are caused by Earth's rotation.

c.450 B.C.

Anaxagoras, Greek philosopher, offers one of the first atomic theories, saying that all matter consists of atoms or "seeds of life."

c.450 B.C.

Anaxagoras argues that the universe is made entirely of matter in motion.

c.450 B.C.

Empedocles, Greek philosopher, first offers his concept of the composition of matter, postulating that it is made of four elements—earth, air, fire, and water. This notion is adopted by Aristotle and becomes the basis of physical theory for nearly two millennia.

c.450 B.C.

The Greek philosopher Leucippus first states the formal notion of atomism. He argues that upon continuous division of a substance, eventually a point would be reached beyond which further division was impossible. His disciple, the Greek philosopher Democritus ultimately names these small particles *atomos*, meaning indivisible.

c.450 B.C.

Zeno of Elea, Greek philosopher, formulates paradoxes challenging the discreteness of continuous time and space.

c.425 B.C.

Democritus (470–380), Greek philosopher, states his atomic theory that all matter consists of infinitesimally tiny particles that are indivisible. These atoms are eternal and unchangeable, although they can differ in their properties. They can also recombine to form new patterns. His intuitive ideas contain much that is found in modern theories of the structure of matter.

c.380 B.C.

Plato (427–347), Greek philosopher, teaches a geometrical theory of matter on which he elaborates in his *Timaeus*.

c.350 B.C.

Aristotle (384–322), Greek philosopher, offers his doctrine of the elements, stating that all things are composed of a basic material in combination with four qualities—hotness, dryness, coldness, and wetness. This theory eventually suggests the idea of transmutation (the changing of ordinary metals into gold or silvers) and gives rise to alchemy.

c.350 B.C.

Aristotle (384–322), Greek philosopher, rejects the atomism of the Greek philosopher Democritus (470–380 B.), thus condemning it to oblivion until modern times. He also states that a vacuum does not exist in nature and that sound travels by a succession of impacts on the air. Aristotle argues correctly that sound is not conducted in the absence of air and incorrectly that a body will move only as long as it keeps being pushed. He also asserts that heavy bodies fall faster than light ones.

c.350 B.C.

Aristotle reasons that Earth is spherical.

c.350 B.C.

Heracleides describes and calculates Earth's rotation.

c.335 B.C.

First description of equinoxes.

c.325 B.C.

Pytheas argues that tides are caused by motions of the Moon.

c.300 B.C.
Arthasastra, an ancient Indian manual on politics, discusses mining, metallurgy, medicine, pyrotechnics, poisons, and fermented liquors.

c.300 B.C.
Aristarchus argues that Earth revolves around the Sun.

c.300 B.C.
Epicurus (341–270), Greek philosopher, elaborates on the atomism of the Greek philosopher Democritus (470–380 B.), but substitutes the notion of chance for the determinism of Democritus.

c.300 B.C.
Euclid, Greek mathematician, writes a treatise on optics in which he makes optics a part of geometry by dealing with light rays as though they are straight lines. He also offers a theory of reflection which he treats geometrically.

c.300 B.C.
Glass blowing first practiced.

c.300 B.C.
Theophrastus, Aristotle's disciple and the founder of botany, attempts to establish a classification system for plants based upon differences between plant and animal morphology.

c.275 B.C.
Herophilus's younger colleague, Eristratus (c. 310–c. 250), asserts that veins and arteries are connected.

c.265 B.C.
Zou Yan asserts the material universe is composed of five elements including water, metal, wood, fire and earth.

c.260 B.C.
Aristarchus of Samos, distance and size of moon from Earth's shadow during lunar eclipse.

c.260 B.C.
Aristarchus of Samos argues for a Sun-centered (heliocentric) cosmology.

c.260 B.C.
Aristarchus of Samos calculates the ratio Sun-Earth distance/Earth-Moon distance from the angle established at half moon.

c.250 B.C.
Chinese, free bodies move at constant velocity.

c.250 B.C.
Philon, Greek engineer, experiments with air and discovers that it expands when heated.

c.240 B.C.
Erastothenes computes the diameter of Earth, suggests it orbits the Sun.

c.220 B.C.
Archimedes (287–212), Greek mathematician and engineer, writes his *Treatise on Floating Bodies* in which he relates the principle of buoyancy.

c.170 B.C.
Chinese astronomers record observations of Sun spots.

c.150 B.C.
Hipparchus, observes and estimates precession of the equinoxes.

c.130 B.C.
Hipparchus estimates the size of Moon from parallax of eclipse.

c.50 B.C. Lucretius proposes a materialistic, atomistic theory of nature in his poem *On the Nature of Things.* He favors the preformation theory of embryological development.

c.10 Cleomedes, Greek astronomer, discusses the optical properties of water and says that in a similar manner, the Sun may be visible when it has actually gone a bit below the horizon. This is the first consideration of atmospheric refraction until Ptolemy.

c.50 Hero, Greek engineer, formulates the principle of the motive power of steam, building many steam-powered devices. He also writes of the five simple machines—lever, pulley, wheel, inclined plane, and wedge—and extends and generalizes the law of the lever. He also maintains correctly that air takes up space and is compressible.

c.70 Roman author and naturalist Pliny the Elder (23–79) writes his influential *Natural History*, a vast compilation combining observations of nature, scientific facts, and mythology. Naturalists will use his work as a reference book for centuries.

c.150 Ptolemy publishes geocentric model with Earth at the center of the solar system.

c.150 Ptolemy, Greek astronomer, writes a treatise on optics in which he considers the refraction of light. He offers an original approach that is both theoretical and experimental.

415 Library of Alexandria is burned by religious zealots, thus destroying the most comprehensive collection of ancient and classical scholarship in science and the arts. Much of the recorded knowledge of Western Civilization was lost.

517 Johannes Philoponus (c.490–570), Alexandrian philosopher, also called John the Grammarian, rejects Aristotle's idea that a body will only move as long as it pushed and offers his own theory of motion. He says that a body will keep moving in the absence of friction or as long as nothing opposes it. He argues that this is why the stars continue to move.

c.850 Al-Kindi (801–866), Arab physicist, writes a treatise on optics and the reflection of light. He also studies meteorology, the tides, and specific weights.

c.890 Al-Razi identifies Andromeda galaxy.

c.1000 Alhazen (965–1038), Arabian physicist, rejects the idea that people see because their eyes send out a light which reflects back from an object. He argues correctly that light comes from the Sun or another source, and reflects from the object into the eye. He studies all aspects of light, especially reflection and refraction, and also offers an exploration of rainbow formation.

c.1025 Al-Biruni (973–1048), Arab physician, astronomer, and mathematician, makes a fairly accurate calculation of the specific weights of eighteen precious stones and metals. He uses the methods employed by Archimedes.

1054 Supernova of Crab Nebula recorded in China and by Native Americans.

1121 Al-khazini argues that gravity acts towards Earth’s center.

1137 Abu Ja’far Alchazin (Al Khazin), Arab mathematician and astronomer, writes a book in which he offers tables of specific densities and a general description of the laws of gravity.

c.1144 First translations of Arabic alchemical manuscripts in Spain, introducing European scholars to alchemy.

c.1225 Robert Grosseteste (1175–1253), English scholar, studies optics and experiments with mirrors and lenses. He attempts to explain the rainbow and argues that light is the basic substance of the universe. He is also the teacher of the English scholar, Roger Bacon (1220–1292).

c.1267 Roger Bacon (1214–1292), English philosopher and scientist, asserts that natural phenomena should be studied empirically.

1269 Pierre de Maricourt experiments with magnets and compass. Discovery that a magnet is encircled by lines which terminate on two magnetic poles.

c.1270 Witelo (1230–1275) of Silesia, also called Vitellio, writes his *Perspectiva*, a systematic treatment of the optics of the Arabian physicist, Alhazen (965–1038). It deals with refraction and reflection as well as the twinkling of stars (caused by motion).

1304 Theodoric of Freibourg conducts experiments to investigate rainbows.

c.1325 William of Ockham (1280–1349), English scholar, argues strongly for the importance of empiricism and lays down the rule called *Ockham’s razor*. According to this rule, when two theories equally fit all observed facts, the one requiring the fewest or simplest assumptions is to be accepted as more valid.

c.1350 Jean Buridan (1300–1385), French philosopher, refutes the Aristotelian notion that an object in motion requires a continuous force, and maintains that only an initial impetus is required. He anticipates Newton’s first law of motion by saying that the celestial bodies stay in motion in this manner.

c.1500 Leonardo da Vinci (1452–1519), Italian artist and inventor, experiments with hydrostatics and diffraction and offers a version of the principle of inertia (which will not come until the time of Galileo).

1510 Two German books lay the foundation for industrial chemistry. *Bergwerkb’chlein* is dedicated to mineralogy and *Probierb’chlein* focuses on chemical tests and introduces quantitative concepts.

1512 Copernicus advances heliocentric model that includes assertion that the planets orbit the Sun.

c.1525 Paracelsus (1493–1541), Swiss physician and alchemist, uses mineral substances as medicines. Denying Galen’s authority, Paracelsus teaches that life is a chemical process.

1543 Andreas Vesalius publishes his epoch-making treatise *The Fabric of the Human Body.* Although Vesalius generally accepts Galenic physiological doctrines and ideas about embryology, Vesalius is later regarded by many as the founder of modern anatomy because he corrected many of Galen’s misconceptions regarding the human body.

1546 Gerardus Mercator describes Earth’s magnetic poles.

1563 Bernard Palissy (c.1510–1589), French potter, publishes his *Recette veritable*, in which he discusses agriculture, geology, mining, and forestry. He discovers the Italian secret of producing majolica (pottery decorated with an opaque tin glaze) and is considered one of the most eminent chemists of France.

1568 Zacharias and Hans Janssen development of the first compound microscope opens new opportunities for the study of structural detail.

1574 Lazarus Ercker (c.1530–1594) of Germany publishes his *Beschreibung aller Furnemisten Mineralischen Ertzt und Bergwercks Arten*, which is the first manual of analytical, metallurgical chemistry. His text is especially valuable to the practicing assayers.

1574 Tycho Brahe argues that a comet he discovered lies beyond the Moon.

1576 Brahe constructs a planetary observatory to accurately record motions of celestial bodies.

1581 Robert Norman, English navigator and instrument maker, publishes a work on the lodestone called *The Newe Attractive*. He discusses the known properties of the magnet and is the first to note that steel does not change its weight when magnetized. He also discovers *magnetic dip*as when he suspends a compass needle to allow vertical movement and notes that it points down toward Earth. This is later used by Gilbert.

1584 Giordano Bruno argues that stars are suns with other planets.

1586 Simon Stevin (1548–1620), Dutch mathematician, publishes a report of his experiment in which he refutes the Aristotelian doctrine that heavy bodies fall faster than light ones. He also founds hydrostatics by demonstrating that the pressure on a liquid varies according to how high above Earth's surface it is and not upon the shape of the container that holds it. His demonstrations also eliminate many standard arguments in favor of the existence of perpetual motion.

1587 Galileo Galilei (1564–1642), Italian astronomer and physicist, begins experiments that lead to his law of falling bodies. He uses a gently sloping inclined plane and shows that the rate of fall of a body is independent of its weight. He eventually states correctly that all objects will fall at the same rate in a vacuum. He also shows that a body can move under the influence of two forces at one time.

1591 Thomas Harriot (1560–1621), English mathematician, is the first Westerner to note that snowflakes are hexagonal (six-sided). He does not publish his findings. The Chinese however, document snow flake crystal shapes from the second century B.C.

1592 Galileo develops primitive thermometer.

1592 Galileo argues that the physical laws of Cosmos are the same as those on Earth.

1600 William Gilbert (1544–1603), English physician and physicist, publishes his *De magnete* which is a full account of his extensive investigations on magnetic bodies and electrical attraction. He suggests that the Earth itself is a great magnet, and he is the first to use the terms electric attraction, electrical force, and magnetic pole.

1604 Galileo observes that distance for falling object increases as square of time.

1604 German astronomer and mathematician Johannes Kepler (1571–1630) writes a treatise on optics.

1608 Hans Lippershey develops optical telescope.

1609 Using a telescope, Galileo observes craters and mountains on the Moon.

1609 Kepler theorizes that a force of gravity exists that can exert itself through empty space, and that its strength is related to the size of the bodies involved.

1609 Kepler offers 1st and 2nd laws of planetary motion.

1610 Galileo observes moons of Jupiter.

1610 Jean Beguin (1550–1620) publishes the first textbook on chemistry.

1613 Galileo documents existence and movements of Sunspots.

1630 Jean Rey (1582–1645), French physician, writes on the nature of air and its role in combustion, and lays the foundation for future chemical discoveries. He suggests a possible experiment for weighing air that Galileo actually performs.

1632 Henry Gellibrand (1597–1636), English astronomer and mathematician, publishes his findings that offer the first indication that the Earth's magnetic field slowly changes over time.

1637 Rene Descartes offers physical explanations of refraction, rainbows and clouds.

1638 Galileo publishes his *Discorsi e dimostrazioni mathematiche intorno a due nuovescienze* which lays the foundations of modern mechanics. In it, he formulates what becomes known as the first law of motion (or the law of inertia), as well as the laws of cohesion and strength of materials, and of the pendulum. It also provides a definition of momentum and details the steps or stages of what becomes known as the experimental method. This work marks the end of Aristotelian physics.

1640 Evangelista Torricelli (1608–1647), Italian physicist, writes his *De motu gravium* in which he applies Galileo's laws of motion to fluids and founds the study of hydrodynamics.

1643 Torricelli is the first to create a sustained vacuum when he invents the barometer. He fills a four-foot-long glass tube with mercury and inverts it onto a dish. He observes that not all the mercury flows out and that over time, the level remaining in the tube varies. He concludes correctly that these changes are caused by atmospheric pressure.

1644 Kenelm Digby (1603–1665), English natural philosopher, observes magnetic and electrical attractions as well as acoustic resonance.

1646 Johann Rudolf Glauber (1604–1670), German chemist, publishes the first of his five-volume *Furni novi philosophici*. This work gives his recipes for mineral acids and salts, including "sal mirabile"—

the sodium sulfate residue that formed by the action of sulfuric acid on ordinary salt—that becomes known as "Glauber's salt."

1648 *Ortus medicinae* by Johann Baptista van Helmont (1580–1644), Flemish physician and alchemist, is published posthumously. He is the first to use quantitative methods in connection with a biological problem. He is also the first to recognize that one air-like substance exists, and he names this vapor, or non-solid, "chaos," which in Flemish sounds like "gas."

1648 Blaise Pascal (1623–1662), French mathematician, physicist, and philosopher, conducts his famous experiment on the Puy-de-Dôme mountain and not only verifies Torricelli's experiments, but goes beyond them to demonstrate that air pressure decreases as altitude increases.

1648 Johannes Marcus Marci von Kronland (1595–1667), Bohemian physician, discovers the diffraction of light, but it does not become a recognized fact until Newton's time.

1651 William Harvey publishes a landmark treatise on embryology entitled *On the Generation of Animals*, stating that all living things come from eggs. Harvey demonstrates that oviparous and viviparous generations are analogous to each other. Although Harvey discovers many errors in Aristotle's ideas, he supports the Aristotelian doctrine that generation occurs by epigenesis.

1653 Blaise Pascal (1623–1662), French mathematician, physicist, and philosopher, studies fluids and formulates what comes to be known as Pascal's principle—that the pressure at any point in a liquid is the same in all directions. Pascal's principle forms the basis of the hydraulic press that he also describes in theory. This information is not published until a year after his death.

1660 Vincenzo Viviani (1622–1703), Italian mathematician, and Giovanni Alfonso Borelli (1608–1679), Italian mathematician and physiologist, collaborate on an experiment in which they measure the velocity of sound by using the cannon-flash-and-sound method.

1661 Robert Boyle (1627–1691), English physicist and chemist, publishes his book, *The Sceptical Chymist*. Boyle espouses the experimental method and breaks from the Greek notion of elements.

1662 Boyle announces what becomes known as Boyle's Law, stating that when an ideal gas is under constant pressure, its volume and pressure vary inversely.

1665 Newton experiments with gravity, spectrum of light, invents differential calculus.

1665 Nicolaus Steno (1638–1686), Danish anatomist and geologist, briefly states what is now called the first law of crystallography. Also called the law of the constancy of crystalline angles, it states that crystals of a specific substance have fixed characteristic angles at which the faces, however distorted, always meet.

1665 Robert Hooke publishes *Micrographia*, an account of observations made with the new instrument known as the microscope. Hooke presents his drawings of the tiny box-like structures found in cork and calls these tiny structures "cells." Although the cells he observes are not living, the name is retained. He also describes the streaming juices of live plant cells.

1666 Isaac Newton begins work on laws of mechanics and gravitation.

1666 Robert Boyle (1627–1691), English physicist and chemist, publishes his *Hydrostatical Paradoxes* in which he details his experiments with fluids and refutes the old doctrine that a light liquid can exert no pressure against a heavier fluid.

1669 Johann Joachim Becher (1635–1682), German chemist, publishes his *Physica subterranea*, in which he is the first to attempt the formulation of a general theory of chemistry. His concept of "terra pinguis" as the substance in air that burns forms the basis of the later phlogiston theory.

1671 Robert Boyle (1627–1691), English physicist and chemist, produces hydrogen by dissolving iron in hydrochloric or sulfuric acid, but he is unaware of his achievement.

1672 Isaac Newton (1642–1727), English scientist and mathematician, publishes his letter on light in the Royal Society's *Philosophical Transactions*. This letter, which is his first scientific publication, details his prism experiments of 1666 and offers findings that reveal for the first time the nature of light. He recounts how he let a ray of sunlight enter a darkened room through a small hole and then passed the ray through a prism onto a screen. The ray was refracted and a band of consecutive colors in rainbow order appeared. He then passed each separate color through another prism and noted that although the light was refracted, the color did not change. From this, he deduced that sunlight (or white light) consists of a combination of these colors. Later he elaborates further on this ground-breaking experiment.

1673 Christiaan Huygens (1629–1695), Dutch physicist and astronomer, publishes his *Horologium oscillatorium* in which he details his invention of the pendulum, or grandfather, clock. He employs Galileo's principle of isochronicity and ingeniously adapts it to the inner workings of a clock, beginning the era of accurate timekeeping that is so important to the advancement of physics. This highly original work not only demonstrates great mechanical ability but superior mathematical theorizing as well.

1674 Hennig Brand (c.1630–c.1692), German chemist, discovers phosphorus, which he finds in urine. This is the first discovery of an element that was not known in any earlier form.

1674 Robert Hooke attempts to explain planetary motion as a balance of centrifugal force and gravitational attraction.

1675 Giovanni Cassini, Saturn has separated rings which must be composed of small objects.

1675 Nicolas Lémery (1645–1715), French chemist and physician, publishes his *Cours de chymie*, which becomes the authoritative textbook on chemistry for the next 50 years. He is an adherent of Boyle's, and advocates the experimental method.

1676 Edmé Mariotte (1620–1684), French physicist, independently formulates Boyle's law and adds an important qualification to it. Like Boyle, he notes that air expands with rising temperature and contracts with falling temperature, but he adds that the inverse relationship between temperature and pressure only holds if the temperature is kept constant. Because of this, Boyle's law is called Mariotte's law in France.

1676 Gottfried Wilhelm Leibniz (1646–1716), German philosopher and mathematician, criticizes Descartes' ideas of motion and formulates his own theory of dynamics which substitutes kinetic energy for the conservation of movement.

1676 Olaus Roemer measures the speed of light by observing Jupiter's moons.

1676 Robert Hooke, law of elasticity and springs.

1678 Christiaan Huygens writes about wave theory of light.

1678 Huygens discovers polarization of light.

1680 Isaac Newton demonstrates that inverse square law implies elliptical orbits.

1681 Johann Joachim Becher (1635–1682), German chemist, obtains tar from the distillation of coal. He also suggests that sugar is necessary for fermentation.

1683 Edmund Halley (1656–1742), English astronomer, states that Earth's magnetism is caused by four poles of attraction, two of them being in each hemisphere near each pole of Earth.

1684 Isaac Newton (1642–1727), English scientist and mathematician, provides the first summary exposition of his theory of gravitation in a memoir entitled *Demotu corporum*. He expands on it later in his 1687 *Principia*.

1686 Edmund Halley (1656–1742), English astronomer, develops a reliable formula that links the altitudes of various localities with the atmospheric pressure measured there. His altimetric formula is one of the first practical applications of the new barometric discoveries.

1687 Denis Papin (1647–1712), French physicist, publishes a work in which he offers details on the use of steam to drive a piston in a cylinder which eventually becomes the basic design for an early steam engine. He never built one of his own design.

1687 English physicist Sir Isaac Newton (1642–1727) publishes a law of universal gravitation in his important and influential work *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy)*. Newton articulates three laws of motion. Still widely regarded as the greatest scientific work ever written, *Principia* states that the entire world is subsumed under a single set of laws. They are: (1) a body remains at rest unless it is compelled to change by a force impressed upon it; (2) the change of motion (the change of velocity times the mass of the body) is proportional to the forces impressed; and (3) to every action there is an equal and opposite reaction. From these laws he then deduces his law of universal gravitation. In its simplest form, Newton's law of universal gravitation states that bodies with mass attract each other with a force that varies directly as the product of their masses and inversely as the square of the distance between them.

1688 John Clayton (1657–1725), English cleric, obtains methane and recognizes its flammable nature.

1690 Christiaan Huygens (1629–1695), Dutch physicist and astronomer, publishes his *Traité: de la lumiére* in which he states his wave theory of light. This unpopular theory sees light as a longitudinal wave that undulates in the direction of its motion much as a sound wave does. The worth of this theory is not understood foray full century.

1690 Christiaan Huygens, principle of Huygens, secondary waves.

1690 Huygens publishes his (wave) theory of light.

1690 John Locke, knowledge comes only from experience and sensations.

1699 Guillaume Amontons (1663–1705), French physicist, publishes his observations on gases. In his work on different gases, he shows that each gas changes in volume by the same amount for a given change in temperature. Implied in this is the notion of absolute zero at which gases can contract no further.

1702 Wilhelm Homberg (1652–1715), German physician, discovers boric acid, which he calls “sedative salt.”

1704 Isaac Newton (1642–1727), English scientist and mathematician, publishes his *Opticks* which is a comprehensive work containing his main discoveries on the nature of light and color as well as his particle, or corpuscular, theory flight.

1709 John Freind (1675–1728), English physician and chemist, publishes *Praelectiones chemicae*, one of the earliest attempts to use Newtonian principles to explain chemical phenomena.

1714 Gabriel Daniel Fahrenheit (1686–1736), German-Dutch physicist, invents the mercury thermometer, the first accurate thermometer. His use of mercury instead of alcohol means that temperatures far above the boiling point of water and well below its freezing point can be measured (since mercury has a higher boiling point than alcohol). He also invents the Fahrenheit temperature scale in which the freezing point of water is 32 degrees and the boiling point is 212 degrees. He arrives at these numbers by adding salt to water to find its lowest freezing point which he calls zero.

1718 Edmund Halley measures motion of stars.

1718 Etienne-François Geoffroy (1672–1731), French apothecary, publishes his *Tables des différens rapports*, which offers a table of affinities between various acids and alkalis or metals. Chemistry eventually accepts his prophetic concept of affinity.

1729 Pierre Bouguer (1698–1758), French physicist, publishes his *Essai d’optique sur la gradation de la lumièere* in which he makes some of the earliest measurements in astronomical photometry. He also investigates the absorption of light in the atmosphere and formulates what comes to be known as Bouguer’s law. This concerns the attenuation of a light beam upon passage through a transparent medium.

1730 René Antoine Ferchault de Réaumur (1683–1757), French naturalist and physicist, develops a thermometer independently of Fahrenheit and establishes what comes to be known as the Reaumur temperature scale. This system has zero degrees as the freezing point of water and 80 degrees as the boiling point of water at normal atmospheric pressure.

1731 Rene Reaumur, alcohol/water thermometer.

1732 Herman Boerhaave (1668–1738), Dutch physician, publishes his *Elementa chemicae*, whose comprehensiveness makes it the most popular chemical textbook for many decades. It serves chemistry as a great teaching book and presents a concise outline of all chemical knowledge.

1732 Pierre Louis Moreau de Maupertuis (1698–1759), French mathematician, publishes his *Discours sur la figure des astres* in which he predicts the shape of Earth using Newtonian mechanics.

1733 Charles François de Cisternay Du Fay (1698–1739), French physicist, discovers that two electrified objects sometimes attract and sometimes repel each other. He notes that their means of being charged seems to be the difference and states that there are two types of electricity, *resinous* and *vitreous*. He formulates the basic electrical law that “like charges repel and unlike charges attract.” Later, American statesman and scientist, Benjamin Franklin (1706–1790) calls these two types of electricity *positive* and *negative*.

1733 Georg Brandt (1694–1768), Swedish chemist, publishes the first accurate and complete study of arsenic and its compounds.

1735 Carl Linnaeus publishes his *Systema Naturae, or The Three Kingdoms of Nature Systematically Proposed in Classes, Orders, Genera, and Species*, a methodical and hierarchical classification of all living beings. He develops the binomial nomenclature for the classification of plants and animals. In this system, each type of living being is classified in terms of genus (denoting the group to which it belongs) and species (its particular, individual name). His classification of plants is primarily based on the characteristics of their reproductive organs.

1738 Daniel Bernoulli (1700–1782), Swiss mathematician, publishes his *Hydrodynamica* containing his kinetic theory of gases. This treatise becomes a work of major importance in both physics and chemistry. This is the first attempt at an explanation of the behavior of gases, which, he assumes, are composed of a vast number of tiny particles.

1739 Georg Brandt, element cobalt.

1742 Anders Celsius (1701–1744), Swedish astronomer, applies a new scale to his thermometer by dividing the temperature difference between the boiling and freezing points of water into an even 100 degrees (with zero at the boiling point, but eventually this is reversed). His system becomes known as the centigrade scale and eventually is adopted internationally by scientists.

1742 Anton Svab (1703–1768) of Sweden, also known as Swab, distills zinc from the alloy calamine.

1743 Alexis Claude Clairaut (1713–1765), French mathematician, publishes his *Theorie de la figure de la terre* in which he definitively discusses a rotating body in the shape of the Earth and how it acts under the influence of gravity and centrifugal force.

1746 Leonhard Euler (1707–1783), Swiss mathematician, argues against the particle theory of light and suggests correctly that light has a wave form and that color depends on the length of that wave.

1750 Thomas Wright, Milky Way could be due to slab like distribution of stars.

1752 Benjamin Franklin (1706–1790), American statesman and scientist, flies a kite carrying a pointed wire in a thunderstorm and attempts to test his theory that atmospheric lightning is an electrical phenomenon similar to the spark produced by an electrical frictional machine. To the kite he attaches a silk thread with a metal key at the end, and as lightning flashes, he puts his hand near the key that sparks, just as a Leyden jar would. He proves his point in this extremely dangerous experiment.

1754 Joseph Black's discovery of carbon dioxide establishes that there are gases other than air.

1754 Pierre-Louis Moreau de Maupertuis suggests that species change over time, rather than remaining fixed.

1756 John Canton (1718–1772), English physicist, begins three years of careful weather observations and finds that on days when the aurora borealis is very noticeable, a compass needle becomes irregular. This is the first observation of what become known as magnetic storms.

1757 Albrecht von Haller 1757–1766), publishes the first volume of his eight-volume *Elements of Physiology of the Human Body*, subsequently to become a landmark in the history of modern physiology.

1758 Axel Fredrick Cronstedt (1722–1756), Swedish chemist, initiates the classification of minerals by their chemical structure as well as by their appearance. He notes four kinds of minerals: earths, metals, salts, and bitumens.

1760 Lagrange formulates principle of least action.

1766 Henry Cavendish (1731–1810), English chemist and physicist, publishes a paper on "Factitious Airs" in the Royal Society's Philosophical Transactions, which relates his discovery of hydrogen, or what he calls "inflammable" air.

1772 Joseph Priestley (1733–1804), English chemist, experiments with "fixed air" and writes his "Directions for Impregnating Water with Fixed Air," in which he details the production of seltzer water by using carbon and water. The distinctive taste of the seltzer, or soda, water brings Priestley much fame.

1774 Antoine-Laurent Lavoisier (1743–1794), French chemist, discovers that oxygen is consumed during respiration.

1774 Manganese is discovered by Swedish mineralogist Johann Gottlieb Gahn (1745–1818) and Karl Wilhelm Scheele (1742–1786), Swedish chemist.

1775 Antoine-Laurent Lavoisier (1743–1794), French chemist, publishes his "Memoire," which contains his first major disavowal of the phlogiston theory, as well as a revision of his combustion theory.

1777 Lavoisier argues that chemical compounds are composed of discrete elements.

1777 Coulomb invents torsion balance (measuring charge).

1780 Lazzaro Spallanzani carried out experiments on fertilization in frogs and attempted to determine the role of semen in the development of amphibian eggs.

1781 William Herschel discovers Uranus.

1782 Torbern Olaf Bergman (1735–1824), Swedish mineralogist, publishes his *Skiagraphia regni mineralis*, in which he classifies minerals into four main groups: salts, earths, metals, and inflammable bodies.

1783 Antoine-Laurent Lavoisier (1743–1794), French chemist, and Pierre-Simone de Laplace (1749–1827), French astronomer and mathematician, jointly publish a paper, "Memoire sur la chaleur," which lays the foundations of thermochemistry. They demonstrate that the quantity of heat required to decompose a compound into its elements is equal to the heat evolved when that compound was formed from its elements.

1783 Antoine-Laurent Lavoisier (1743–1794), French chemist, repeats the experiment conducted by Cavendish in 1766 and realizes that he is dealing with a separate gas. He calls this flammable gas "hydrogen," from the Greek phrase meaning "giving rise to water."

1783 Horace Benedict de Saussure (1740–1799), Swiss physicist, publishes his *Essais sur l'hygrometrie* in which he details his invention of a hygrometer that uses human hair for measuring humidity. He also discusses the general principles of hygrometry.

1783 Juan Jose d'Elhuyar (1754–1796) and his younger brother, Don Fausto d'Elhuyar (1755–1833), both Spanish mineralogists, analyze a mineral called wolframite and discover a new metal, tungsten.

1785 James Hutton (1726–1797) proposes uniformitatianism as theoretical basis to interpret geological history of the earth.

1785 Charles Augustin de Coulomb (1736–1806), French physicist, publishes the first of seven papers in which he establishes the basic laws of electrostatics and magnetism. Using his newly invented torsion balance, he determines that Newton's law of inverse squares also applies to electrical and magnetic attraction and repulsion. He states that the degree of attraction or repulsion depends on the amount of electric charge or the magnetic pole strength.

1787 Antoine-Laurent Lavoisier (1743–1794), French chemist, publishes *Methode de la nomenclature chimique* in collaboration with French chemist, Louis-Bernard Guyton de Morveau (1737–1816). This book gives the new chemistry a modern terminology and changes chemical nomenclature to correspond to the new antiphlogiston theory.

1787 Ernst Florens Friedrich Chladni (1756–1827), German physicist, publishes his *Theorie des Klanges* in which he is the first to discover the quantitative relationships that rule the transmission of sound. He also creates *Chladni's figures* by spreading sand on thin plates and vibrating them, producing complex patterns from which much is learned about vibrations. He is considered the father of acoustics.

1787 Jacques-Alexandre Charles (1746–1823), French physicist, demonstrates that different gases all expand by the same amount with a given rise in temperature if the pressure is held constant. This becomes known as Charles's law, and also Gay-Lussac's law.

1789 Martin Heinrich Klaproth (1743–1817), German chemist, discovers uranium in pitchblende. The Curies will refine this same substance in 1898. Later the same year, Klaproth discovers the element zirconium in the mineral zircon.

1790 France introduces the metric system.

1795 James Hutton publishes Theory of the Earth (in Scotland).

1795 Martin Heinrich Klaproth (1743–1817), German chemist, isolates a new metal and names it titanium, after the Titans of Greek mythology. He gives full credit to English mineralogist William Gregor (1761–1817), who first discovered it in 1791.

1796 Erasmus Darwin, grandfather of Charles Darwin and Francis Galton, publishes his *Zoonomia.* In this work, Darwin argues that evolutionary changes are brought about by the mechanism primarily associated with Jean-Baptiste Lamarck, that is, the direct influence of the environment on the organism.

1798 Henry Cavendish (1731–1810), English chemist and physicist, is the first to calculate Earth's mass. He does this by obtaining what Isaac Newton had not provided—a value for the gravitational constant. He builds a model with light balls and large, heavy ones and uses a sensitive wire to calculate the strength of the attraction between the two. Once he obtains this constant value, he calculates Earth's mass close to modern value.

1801 William Hyde Wollaston (1766–1828), English chemist and physicist, establishes that frictional and galvanic electricity are identical. He also discovers, independently of Ritter, the existence of invisible light beyond violet light (ultraviolet light).

1802 John Dalton introduces modern atomic theory into the science of chemistry.

1802 Thomas Thomson (1773–1852), Scottish chemist, publishes his *System of Chemistry* and introduces a system of symbols for individual minerals using the first letters of their names.

1802 Thomas Young (1773–1829), English physicist and physician, performs his classic experiment on interference in which sunlight is made to pass through two pinholes in an opaque screen. With a wave interpretation of his observations, he is able to provide the first quantitative values for the length of light waves.

1803 John Dalton (1766–1844), English chemist, states the law of multiple proportions which applies to two elements that could combine in more than one way. He also states his atomic theory that says that all elements are composed of extremely tiny, indivisible, indestructible atoms, and that all the known substances are composed of some combination of these atoms. He finally states that these atoms differ from each other only in mass, and that this difference can be measured.

1803 Louis Poinsot (1777–1859), French mathematician, publishes his *Éléments de statique* which contains his theory of couples (two parallel forces of equal magnitude but opposite direction form a couple). He also introduces the concept of torque.

1803 Smithson Tennant, elements osmium and iridium.

1803 William Henry (1774–1836), English physician and chemist, proposes what becomes Henry's law, stating that the amount of gas absorbed by a liquid is in proportion to the pressure of the gas above the liquid, provided no chemical reaction occurs.

1805 John Dalton (1766–1844), English chemist, publishes the first table of atomic weights and invents a new system of chemical symbols.

1805 Joseph-Louis Gay-Lussac (1778–1850), French chemist, establishes that precisely two volumes of hydrogen combine with one volume of oxygen to form water.

1811 Amedeo Avogadro (1776–1856), Italian physicist, first proposes his theory of molecules, which is confirmed much later by modern chemistry. He states that equal volumes of all gases contain the same number of molecules if they are under the same pressure and temperature.

1813 Sowerby publishes Sowerby's Mineral Conchology.

1815 William Smith publishes first geological map of UK.

1818 Jöns Jakob Berzelius (1779–1848), Swedish chemist, discovers selenium, publishes a table of atomic weights, and offers a system of chemical symbols. His weight table is based on a standard 100 for oxygen and becomes accepted in the twentieth century. His symbols use one or two letters of the Latin name and are essentially also retained in the twentieth century.

1819 Eilhardt Mitscherlich (1794–1863), German chemist, discovers isomorphism. This chemical theory states that compounds of similar composition tend to crystallize together, or, conversely, that compounds with the same crystal form are analogous in chemical composition. This law becomes useful in establishing atomic weights.

1819 Øersted discovers electromagnetism.

1820 André Marie Ampère (1775–1836), French mathematician and physicist, extends Ørsted's work and formulates one of the basic laws of electromagnetism. He discovers that two parallel wires each carrying a current attract each other if the currents are in the same direction, but they repel each other if in the opposite direction. He concludes that magnetism is the result of electricity in motion.

1820 Hans Christian Ørsted (1777–1851), Danish physicist, experiments with a compass and electricity and demonstrates that a current of electricity creates a magnetic field. He announces his discovery in a short article. This is the first time a real connection can be shown between electricity and magnetism, and it founds the new field of electromagnetism.

1821 Faraday proposes flux line picture for electricity and magnetism.

1821 Friedlieb Ferdinand Runge (1795–1867), German chemist, discovers caffeine.

1822 Omalius d'Holloy names the Cretaceous.

1823 Mary Anning discovers first complete pterodactyl in Lyme Regis in Dorset UK.

1824 Nicolas Léonard Sadi Carnot (1796–1832), French physicist, publishes his *Réflexions sur la puissance motrice du feu* in which he is the first to consider quantitatively the manner in which heat and work are interconverted. This highly original work also introduces the important concept of cyclic operations and the principle of reversibility. Although this work founds the science of thermodynamics, or the movement of heat, it is neglected for ten years.

1825 Hans Christian Ørsted (1777–1851), Danish physicist, isolates aluminum through a four-step process that involves a vacuum.

1826 André Marie Ampère (1775–1836), French mathematician and physicist, publishes his *Mémoire sur la théoriemathématique des phénomàmes électrodynamiques*in which he offers the mathematical laws that govern the new field of electricity in motion and founds the study of electrodynamics.

1826 James Cowles Prichard presented his views on evolution in the second edition of his book *Researches into the Physical History of Man* (first edition 1813). These ideas about evolution were suppressed in later editions.

1827 Brown discovers "Brownian Motion".

1830 Charles Lyell publishes *Principles of Geology* and argues Earth is a least millions of years old.

1830 Joseph Henry (1797–1878), American physicist, discovers the principle of electromagnetic induction, showing how an electric current in one coil may set up a current in another through the development of a magnetic field. He puts off further work on this discovery until the following summer, and in the intervening time, the English physicist and chemist, Michael Faraday (1791–1867), publishes his discovery first.

1831 Charles Robert Darwin begins his historic voyage on the H.M.S. *Beagle* (1831–1836). His observations during the voyage lead to his theory of evolution by means of natural selection.

1834 F. Von Alberti names the Triassic Period.

1840 Friedrich Gustav Jacob Henle publishes the first histology textbook, *General Anatomy.* This work includes the first modern discussion of the germ theory of communicable diseases.

1840 Germain-Henri Hess (1802–1850), Swiss-Russian chemist, formulates the law that states that the quantity of heat evolved in a chemical change is the same no matter what chemical route the reaction takes (through a single stage or through many stages. This becomes known as Hess's law.

1840 Jöns Jakob Berzelius (1779–1848), Swedish chemist, first introduces the term “allotropy” to describe the existence of different varieties of an element. He converts charcoal into graphite and declares that the same element may have in different forms.

1840 Karl Bogislaus Reichert introduces the cell theory into embryology. He proves that the segments observed in fertilized eggs develop into individual cells, and that organs develop from cells.

1840 Louis Agassiz publishes his *Etudes sur les glaciers*. Also discovers glacial feature in Scotland away from an ice covered area and advances the theory of glaciation.

1840 Murchison and Sedgwick name the Devonian Period after the county of Devon in UK.

1840 Rudolf Albert von Kölliker establishes that spermatozoa and eggs are derived from tissue cells. He attempts to extend the cell theory to embryology and histology.

1841 Murchison names the Permian Period.

1842 Charles Robert Darwin writes out an abstract of his theory of evolution, but he does not plan to have this theory published until after his death.

1842 Christian Johann Doppler (1803–1853), Austrian physicist, discovers the effect of motion of the source or observer on the observed frequency of sound waves. This mathematical relationship that relates their pitch to the relative motion of the source or observer is called the Doppler effect.

1846 Johann Gottfried Galle discovers Neptune, accounting for observed perturbations in the motion of Uranus.

1848 William Thomson (1824–1907), later known as Lord Kelvin, Scottish mathematician and physicist, explores the concept of absolute zero at which the volume of a gas would be reduced to zero and explains it by stating that it is not that the volume reaches zero but rather that the motion of the gas’s molecules stops. He then proposes a new temperature scale with its zero mark at absolute zero and its degrees equal to those on the centigrade scale. It becomes known as the kelvin scale. He also coins the term *thermodynamics*.

1850 Michael Faraday experiments to find link between gravity and electromagnetism fail.

1850 Rudolph Julius Emanuel Clausius (1822–1888), German physicist, publishes a paper which contains what becomes known as the second law of thermodynamics, stating that, “heat cannot, of itself, pass from a colder to a hotter body.” He later refines the concept.

1850 Thomas Graham (1805–1869), Scottish physical chemist, studies the diffusion of a substance through a membrane (osmosis) and first distinguishes between crystalloids and colloids. He becomes the founder of colloidal chemistry.

1851 Armand Hippolyte Fizeau (1819–1896), French physicist, measures the speed of light as it flows with a stream of water and as it goes against the stream. He finds that the velocity of light is higher in the former.

1851 Jean Bernard Léon Foucault (1819–1868), French physicist, conducts his spectacular series of experiments associated with the pendulum. He swings a heavy iron ball from a wire more than 200 feet long and demonstrates that the swinging pendulum maintains its plane while Earth slowly twists under it. The crowd of spectators who witnesses this demonstration come to realize that they are watching Earth rotate under the pendulum — experimental proof of a moving Earth.

1851 William Thomson (1824–1907), later known as Lord Kelvin, Scottish mathematician and physicist, publishes *On the Dynamical Theory of Heat* in which he explores Carnot’s work and deduces that all energy tends to rundown and dissipate itself as heat. This is another form of the second law of thermodynamics and is advanced further by Clausius at about the same time. Kelvin’s work is considered the first nineteenth-century treatise on thermodynamics.

1852 Abraham Gesner (1797–1864), Canadian geologist, prepares the first kerosene from petroleum. He obtains the liquid kerosene by the dry distillation of asphalt rock, treats it further, and calls the product kerosene after the Greek word *keros*, meaning oil.

1852 Alexander William Williamson (1824–1904), English chemist, publishes his study which shows for the first time that catalytic action clearly involves and is explained by the formation of an intermediate compound.

1852 Edward Frankland (1825–1899), English chemist, announces the theory of valence, in which he states that each type of atom has a fixed capacity for combining with other atoms. This concept will lead eventually to Mendeleev’s Periodic Table.

1852 James Joule (1818–1889) and William Thomson (1824–1907), both English physicists, show that when a gas is allowed to expand freely, its temperature drops slightly. This becomes known as the Joule–Thomson effect and is evidence that molecules of gases have a slight attraction for other molecules. Overcoming this attraction uses energy and causes a drop in temperature.

1852 Jean Bernard Léon Foucault (1819–1868), French physicist, learns from his pendulum experiment and invents the gyroscope. He sets a wheel within a heavy rim in rotation and sees that when tipped, it is set right again by the force of gravity.

1853 Anders Jonas Ångström (1814–1874), Swedish physicist, demonstrates that the rays emitted by an incandescent gas have the same refrangibility (ability to be refracted) as the rays absorbed by the same gas.

1853 Hans Peter Jorgen Julius Thomsen (1826–1901), Danish chemist, works out a method of manufacturing sodium carbonate from the mineral cryolite. This mineral will soon become important to the production of aluminum.

1853 Johann Wilhelm Hittorf (1824–1914), German chemist and physicist, offers the notion of the transport number as he suggests that ions in a solution with a current running through it travel at different speeds.

1853 William John Macquorn Rankine (1820–1872), Scottish engineer, introduces into physics the concept of potential energy, also called the energy of position.

1854 George Airy, Estimate of Earth mass from underground gravity.

1854 Gregor Mendel begins studying 34 different strains of peas. He selects 22 kinds for further experiments. From 1856 to 1863, Mendel grows and tests over 28,000 plants and analyzes seven pairs of traits.

1855 Charles-Adolphe Wurtz (1817–1884), French chemist, develops a method of synthesizing long-chain hydrocarbons by reactions between alkyl halides and metallic sodium. This method is called the Wurtz reaction.

1855 James Clerk Maxwell, mathematics of Faraday's lines of force.

1855 Johann Heinrich Wilhelm Geissler (1814–1879), German inventor, devises a mercury pump that produces a much better vacuum than old piston pumps. Called Geissler tubes, they make possible a more advanced study of electricity and eventually of the atom. It is with Geissler tubes that the English physicist, Joseph John Thomson (1856–1940), performs his famous experiments elucidating the nature of electrons.

1855 William Parsons, spiral galaxies.

1856 Neanderthal fossil identified.

1857 Louis Pasteur demonstrates that lactic acid fermentation is caused by a living organism. Between 1857 and 1880, he performs a series of experiments that refute the doctrine of spontaneous generation. He also introduces vaccines for fowl cholera, anthrax, and rabies, based on attenuated strains of viruses and bacteria.

1857 Rudolf Julius Emmanuel Clausius (1822–1888), German physicist, offers a new explanation of evaporation in terms of molecules and their velocities. He shows that evaporation produces a loss of energy in the liquid and a decrease in temperature.

1858 Charles Darwin and Alfred Russell Wallace agree to a joint presentation of their theory of evolution by natural selection.

1858 Friedrich August Kekulé von Stradonitz (1829–1896), German chemist, and Archibald Scott Couper (1831–1892), Scottish chemist, first develop symbols to represent the atom is always tetravalent (meaning always combines with four other atoms).

1858 Hermann Ludwig Ferdinand von Helmholtz (1821–1894), German physiologist and physicist, publishes his study on the integrals of hydrodynamic equations that express whirling motion. This becomes the point of departure for new ideas on the structure of matter that eventually replaces the old atomistic concepts.

1858 Julius Plücker (1801–1868), German mathematician and physicist, sends an electric current through a vacuum and describes fluorescent effects in detail. He also discovers that the glow shifts position when placed in the field of an electromagnet. This is the very beginning of an awareness of subatomic particles.

1859 Gustav Robert Kirchhoff (1824–1887), German physicist, after discovering the relation between emission and absorption spectra, concludes that the ratio of the emissive and absorptive powers of a body at each wave length is the same for all bodies at the same temperature. This becomes known as Kirchhoff's law.

1859 James Clerk Maxwell (1831–1879), Scottish mathematician and physicist, studies the rings of Saturn and produces the first extensive mathematical development of the kinetic theory of gases. He shares this discovery of the distribution of molecular speeds in a gas with Ludwig E. Boltzmann (1844–1906), Austrian physicist, who accomplishes the same independently. It comes to be known as the Maxwell–Boltzmann theory of gases.

1859 Urbain Le Verrier, anomolous perihelion shift of Mercury.

1860 Cesium is the first element discovered using the newly developed spectroscope. Robert Wilhelm Bunsen (1811–1899), German chemist, and Gustav Robert Kirchhoff (1824–1887), German physicist, name their new element cesium after its “sky blue” color in the spectrum.

1860 Gustav Robert Kirchhoff (1824–1887), German physicist, introduces the concepts of black bodies and emissivity. A black body is a surface that absorbs all radiation of any wavelength falling on it. Such a body would emit all wavelengths if it were heated to incandescence. This concept later becomes important to quantum theory.

1860 Jean-Servais Stas (1813–1891), Belgian chemist, begins work that leads to an accurate method of determining atomic weights. By 1865, he produces the first modern table of atomic weights using oxygen as a standard.

1860 Robert Wilhelm Bunsen (1811–1899), German chemist, collaborates with Gustav Robert Kirchhoff (1824–1887), German physicist, and they develop the first spectroscope.

1860 Stanislao Cannizzaro (1826–1910), Italian chemist, publishes the forgotten ideas of Italian physicist Amedeo Avogadro (1776–1856)—about the distinction between molecules and atoms—in an attempt to bring some order and agreement on determining atomic weights.

1861 Alexander Mikhailovich Butlerov (1828–1886), Russian chemist, introduces the term “chemical structure” to mean that the chemical nature of a molecule is determined not only by the number and type of a atoms but also by their arrangement.

1861 Friedrich August Kekulé von Stadonitz (1829–1896), German chemist, publishes the first volume of *Lehrbuch der organischen Chemie*, in which he is the first to define organic chemistry as the study of carbon compounds.

1861 Robert Wilhelm Bunsen (1811–1899), German chemist, and Gustav Robert Kirchhoff (1824–1887), German physicist, discover the metal rubidium, using their new spectroscope.

1861 William Crookes (1832–1919), English physicist, discovers the element thallium by using the newly invented spectrum analysis. The following year, it is isolated by French chemist Claude-August Lamy (1820–1878).

1861 William Thomson (1824–1907), later known as Lord Kelvin, Scottish mathematician and physicist, publishes his *Physical Considerations Regarding the Possible Age of the Sun’s Heat* which contains the theme of the *heat death* of the Universe. This is offered in light of the principle of dissipation of energy stated in 1851.

1862 Anders Ångström observes hydrogen in the sun.

1863 Ferdinand Reich (1799–1882), German mineralogist, and his assistant Hieronymus Theodor Richter (1824–1898), examine zinc ore spectroscopically and discover the new, indigo-colored element iridium. It is used in the next century in the making of transistors.

1863 William Huggins, stellar spectra indicate that stars made of same elements found on Earth.

1864 James Clerk Maxwell publishes equations of electromagnetic wave propagation in the ether.

1865 Alexander Parkes (1813–1890), English chemist, produces celluloid, the first synthetic plastic material. After working since the 1850s with nitrocellulose, alcohol, camphor, and castor oil, he obtains a material that can be molded under pressure while still warm. Parkes is unsuccessful at marketing his product, however, and it is left to the American inventor, John Wesley Hyatt (1837–1920), to make it a success.

1865 Johann Joseph Loschmidt (1821–1895), Austrian chemist, is the first to attempt to determine the actual size of atoms and molecules. He uses Avogadro’s hypothesis to calculate the number of molecules in 22.4 liters of gas, and calls the resulting number Avogadro’s number ($6.02x10^{23}$).

1865 Rudolf Julius Emanuel Clausius (1822–1888), German physicist, refines the second law of thermodynamics and first introduces the term *entropy*, stating that the energy in a closed system will always eventually rundown.

1866 August Adolph Eduard Eberhard Kundt (1839–1894), German physicist, invents a method by which he can make accurate measurements of the speed of sound in the air. He uses a *Kundt’s tube* whose inside is dusted with fine powder which is then disturbed by traveling sound waves.

1866 Ernst Heinrich Haeckel publishes his book *A General Morphology of Organisms.* Haeckel summarizes his ideas about evolution and embryology in his famous dictum “ontogeny recapitulates phylogeny.” Haeckel suggests that the nucleus of a cell transmits hereditary information. He introduces the use of the term “ecology” to describe the study of living organisms and their interactions with other organisms and with their environment.

1866 Johann Gregor Mendel (1822–1884), Austrian botanist and monk, discovers the laws of heredity and writes the first of a series of papers on heredity (1866–1869), which formulate the laws of hybridization. His work is disregarded until 1900, when de Vries rediscovers it. Unbeknownst to both Darwin and Mendel, Mendelian laws provide the scientific framework for the concepts of gradual evolution and continuous variation.

1868 Pierre-Jules-César Janssen (1824–1907), French astronomer, studies a total eclipse of the Sun and observes an unknown spectral line. He forwards the data to the English astronomer Joseph Norman Lockyear (1836–1920), who concludes it is an unknown element that he names helium, after the Sun.

1868 William Huggins, Doppler shifts of stellar spectra.

1869 Dimitri Ivanovich Mendeleev (1834–1907), Russian chemist, and Julius Lothar Meyer (1830–1895), German chemist, independently put forth the Periodic Table of Elements, which arranges the elements in order of atomic weights. However, Meyer does not publish until 1870, nor does he predict the existence of undiscovered elements as does Mendeleev.

1871 Charles Robert Darwin published *The Descent of Man, and Selection in Relation to Sex.* This work introduces the concept of sexual selection and expands his theory of evolution to include humans.

1871 John William Strutt Rayleigh (1842–1919), English physicist, discovers that the degree of scattering of light by very fine particles is a function of the wavelength of light. His equation offers a solution to the question of why the sky is blue.

1871 Ludwig Eduard Boltzmann (1844–1906), Austrian physicist, begins work on his mathematical treatment of the second law of thermodynamics, interpreting it in terms of the statistics of molecular motions. His work lays the foundations of statistical mechanics.

1872 Ferdinand Julius Cohn publishes the first of four papers entitled “Research on Bacteria,” which establishes the foundation of bacteriology as a distinct field. He systematically divides bacteria into genera and species.

1873 Franz Anton Schneider describes cell division in detail. His drawings includes both the nucleus and chromosomal strands.

1873 James Clerk Maxwell (1831–1879), Scottish mathematician and physicist, publishes *Treatise on Electricity and Magnetism* in which he identifies light as an electromagnetic phenomenon. He determines this when he finds his mathematical calculations for the transmission speed of both electromagnetic and electrostatic waves are the same as the known speed of light. This landmark work brings together the three main fields of physics—electricity, magnetism, and light.

1873 Johannes Van der Waals (1837–1923), Dutch physicist, offers an equation for the gas laws which contains terms relating to the volumes of the molecules themselves and the attractive forces between them. It becomes known as the Van der Waals equation.

1873 Walther Flemming discovers chromosomes, observes mitosis, and suggests the modern interpretation of nuclear division.

1876 Henry Augustus Rowland (1848–1901), American physicist, establishes for the first time that a moving electric charge or current is accompanied by electrically charged matter in motion and produces a magnetic field.

1876 James Clerk Maxwell (1831–1879), Scottish mathematician and physicist, publishes his *Matter and Motion* in which he considers the categories of space and time and states with great prescience that, “all our knowledge, both of time and place, is essentially relative.”

1876 Josiah Willard Gibbs (1829–1903), American physicist, discovers the phase rule. He arrives at an equation that relates the variables (like temperature and pressure) to different phases (solid, liquid, gas). His work helps lay the foundation for chemical thermodynamics and generally for modern physical chemistry. The rule is later put into practical application by Dutch physical chemist Hendrik Willem Bakhuis Roozeboom (1854–1907).

1877 Astonomer Asaph Hall identifies two moons of Mars.

1880 Carl Oswald Viktor Engler (1842–1925), German chemist, begins his studies on petroleum. He is the first to state that it is organic in origin.

1882 Robert Koch (1843–1910), German bacteriologist, discovers the tubercle bacillus and enunciates “Koch’s postulates,” which define the classic method of preserving, documenting, and studying bacteria.

1883 August F. Weismann begins work on his germplasm theory of inheritance. Between 1884 and 1888, Weismann formulates the germplasm theory that argues that the germplasm is separate and distinct from the somatoplasm. Weismann argues that the germplasm is continuous from generation to generation and that only changes in the germplasm are transmitted to further generations. Weismann proposes a theory of chromosome behavior during cell division and fertilization and predicts the occurrence of a reduction division (meiosis) in all sexual organisms.

1883 Ernst Mach (1838–1916), Austrian physicist, publishes his *Die Mechanik in ihrer Entwickelung historisch-kritisch dargestellt* in which he offers a radical philosophy of science that calls into question the reality of such Newtonian ideas as space, time, and motion. His work influences Einstein and prepares the way for relativity.

1883 Frank Wigglesworth Clarke (1847–1931), American chemist and geophysicist, is appointed chief chemist to the U.S. Geological Survey. In this position, he begins an extensive program of rock analysis and is one of the founders of geochemistry.

1883 George Francis Fitzgerald (1851–1901), Irish physicist, first suggests a method of producing radio waves. From his studies of radiation, he concludes that an oscillating current would produce electromagnetic waves. This is later verified experimentally by Hertz in 1888 and used in the development of wireless telegraphy.

1883 Johann Gustav Kjeldahl (1849–1900), Danish chemist, devises a method for the analysis of the nitrogen content of organic material. His method uses concentrated sulfuric acid and is simple and fast.

1883 Thomas Alva Edison (1847–1931), American inventor, discovers the emission of electrons from hot bodies. He inserts a small metal plate near the filament of a light bulb and finds that the plate draws a current when he connects it to the positive terminal of the light bulb circuit, even though the plate is not touching the filament. Called the Edison effect, this is later a major factor in the invention of the vacuum tube.

1884 Svante August Arrhenius (1859–1927), Swedish chemist, first proposes the concept of ions being atoms bearing electrical charges.

1886 Paul-Louis-Toussint Héroult (1863–1914), French metallurgist, and Charles Martin Hall (1863–1914), American chemist, independently invent an electrochemical process for extracting aluminum from its ore. This process makes aluminum cheaper and forms the basis of the huge aluminum industry. Hall makes the discovery in February of this year, and Héroult achieves his in April.

1886 Roland von Eötvös (1848–1919), Hungarian physicist, first introduces the concept of molecular surface tension. His study of Earth's gravitational field, which leads him to invent a precise torsion balance, results in his proof that inertial mass and gravitational mass are equivalent. This proves to be a major principle in Einstein's general theory of relativity.

1887 Albert Abraham Michelson (1852–1931), German-American physicist, collaborates with the American chemist, Edward Williams Morley (1838–1923), to test the age-old hypothesis that Earth moves through luminiferous ether (the supposed light-carrying element that exists outside or above Earth's atmosphere). They use Michelson's interferometer—that splits a beam of light in two, sends each on a different path, and then reunites them—to test out this idea. The failure of this extremely sensitive instrument to detect even the slightest change in the velocity of light proves that the ether does not exist (for it would have had to change slightly if it had gone through a substance). This result overturns all ether-based theories and makes physicists search for some explanation of the invariance of the speed of light.

1887 Ernst Mach (1838–1916), Austrian physicist, is the first to note the sudden change in the nature of the airflow over a moving object that occurs as it approaches the speed of sound. Because of this, the speed of sound in air (under certain temperature conditions) is called Mach 1. Mach 2 is twice that speed and so on.

1887 Herman Frasch (1851–1914), German-American chemist, patents a method for removing sulfur compounds from oil. Once the foul sulfur smell is removed through the use of metallic compounds, petroleum becomes a marketable product.

1887 Woldemar Voigt, anticipated Lorentz transform to derive Doppler shift.

1888 Heinrich Rudolf Hertz (1857–1894), German physicist, for the first time generates electromagnetic (radio) waves and devises a detector that can measure their wavelength. From this he is able to prove experimentally James Clerk Maxwell's (1831–1879) hypothesis that light is an electromagnetic phenomenon. Hertz's work not only discovers radio waves, but experimentally unites the three main fields of physics—electricity, magnetism, and light.

1890 Hendrik Antoon Lorentz (1853–1928), Dutch physicist, suggests that the atom consists of charged particles whose oscillations can be affected by a magnetic field. This is later confirmed by his pupil, the Dutch physicist, Pieter Zeeman (1865–1943), in 1896.

1891 Edward Goodrich Acheson (1856–1931), American inventor, discovers that carbon heated with clay yields an extremely hard substance. He names it carborundum, and eventually finds it to be a compound of silicon and carbon. For half a century it remains second only to a diamond in hardness, and becomes very useful as an abrasive.

1893 Augusto Righi (1850–1920), Italian physicist, demonstrates that Hertz (radio) waves differ from light only in wavelength and not because of any essential difference in their nature. This helps to establish the existence of the electromagnetic spectrum.

1893 Ferdinand-Frédéric-Henri Moissan (1852–1907), French chemist, produces artificial diamonds in his electric furnace.

1894 Guglielmo Marconi (1874–1937), Italian electrical engineer, uses Hertz's method of producing radio waves and builds a receiver to detect them. He succeeds in sending his first radio waves 30 feet to ring a bell. The next year, his improved system can send a signal 1.5 miles.

1894 John William Strutt Rayleigh (1842–1919), English physicist, and William Ramsay (1852–1916), Scottish chemist, succeed in isolating a new gas in the atmosphere that is denser than nitrogen and combines with no other element. They name it "argon," which is Greek for inert. It is the first of a series of rare gases with unusual properties whose existence had not been predicted.

1895 Pierre Curie (1859–1906), French chemist, studies the effect of heat on magnetism and shows that there is a critical temperature point above which magnetic properties will disappear. This comes to be called the Curie point.

1895 Wilhem Conrad Röntgen (1845–1923), German physicist, submits his first paper documenting his discovery of x rays. He tells how this unknown ray, or radiation, can affect photographic plates, and that wood, paper, and aluminum are transparent to it. It also can ionize gases and does not respond to electric or magnetic fields nor exhibit any properties of light. This discovery leads to such a stream of groundbreaking discoveries in physics that it has been called the beginning of the second scientific revolution.

1895 William Ramsay (1852–1916), Scottish chemist, discovers helium in a mineral named cleveite. It had been speculated earlier that helium existed only in the Sun, but Ramsay proves it also exists on Earth. It is discovered independently this year by Swedish chemist and geologist Per Theodore Cleve (1840–1905). Helium is an odorless, colorless, tasteless gas that is also insoluble and incombustible.

1896 Antoine Henri Becquerel (1852–1908), French physicist, studies fluorescent materials to see if they emit the newly-discovered x rays and discovers instead that uranium produces natural radiation that is eventually called *radioactivity* in 1898 by the Polish-French chemist, Marie Sklodowska Curie (1867–1934).

1897 Joseph John Thomson (1856–1940), English physicist, discovers the electron. He conducts cathode ray experiments and concludes that the rays consist of negatively charged "electrons" that are smaller in mass than atoms.

1898 Marie Sklodowska Curie (1867–1934), Polish-French chemist, discovers thorium, which she proves is radioactive.

1899 Ernest Rutherford (1871–1937), British physicist, discovers that radioactive substances give off different kinds of rays. He names the positively charged ones alpha rays and the negative ones beta rays.

1900 Carl Correns, Hugo de Vries, and Erich von Tschermak independently rediscover Mendel's laws of inheritance. Their publications mark the beginning of modern genetics. Using several plant species, de Vries and Correns perform breeding experiments that paralleled Mendel's earlier studies and independently arrive at similar interpretations of their results. Therefore, upon reading Mendel's publication, they immediately recognized its significance. William Bateson describes the importance of Mendel's contribution in an address to the Royal Society of London.

1900 Friedrich Ernst Dorn (1848–1916), German physicist, analyzes the gas given off by (radioactive) radium and discovers the inert gas he names radon. This is the first clear demonstration that the process of giving off radiation transmutes one element into another during the radioactive decay process.

1900 Hugo Marie de Vries describes the concept of genetic mutations in his book *Mutation Theory.* He uses the term mutation to describe sudden, spontaneous, and drastic alterations in the hereditary material.

1900 Max Karl Ernst Ludwig Planck (1858–1947), German physicist, publishes his classic and revolutionary paper on quantum physics. He tells of his discovery that light or energy is not found in nature as a continuous wave or flow, but is emitted and absorbed discontinuously in little packets, or *quanta*. Further, each quantum, or packet of energy, is indivisible. Planck's new notion of the quantum seemed to contradict the mechanics of Newton and the electromagnetics of Maxwell, and replace them with new rules. In fact, his quantum physics were new rules in a new type of physics—physics of the very fast and the very small. His theory is soon applied (by Einstein) and incorporated (by Bohr), and becomes the watershed between all physics that comes before it (classical physics) and all that is after (modern physics).

1900 Paul Karl Ludwig Drude (1863–1906), German physicist, proposes the first model for the structure of metals. His model explains the constant relationship between electrical conductivity and the heat conductivity in all metals.

1900 Paul Ulrich Villard (1860–1934), French physicist, discovers what are later called gamma rays. While studying the recently discovered radiation from uranium, he finds that in addition to the alpha rays and beta rays, there are other rays, unaffected by magnets, that are similar to x rays, but shorter and more penetrating.

1901 Antoine Henri Becquerel (1852–1908), French physicist, studies the rays emitted by the natural substance uranium and concludes that the only place they could be coming from is within the atoms of uranium. This marks the first clear understanding of the atom as something more than a featureless sphere. It implies a dynamic reality that might also contain electrons. Becquerel's discovery of radioactivity and his focus on the uranium atom make him the father of modern atomic and nuclear physics.

1901 Guglielmo Marconi (1874–1937), Italian electrical engineer, successfully sends radio signal from England to Newfoundland.

1902 Discovery of Tyrannosaurus Rex fossil.

1902 Lapworth names the Ordovician Period after a Welsh Iron Age tribe.

1902 Oliver Heaviside (1850–1925), English physicist and electrical engineer, and Arthur Edwin Kennelly (1861–1939), British-American electrical engineer, independently and almost simultaneously make the first prediction of the existence of the ionosphere, an electrically conductive layer in the upper atmosphere that reflects radio waves. They theorize correctly that wireless telegraphy works over long distances because a conducting layer of atmosphere exists that allows radio waves to follow the Earth's curvature instead of traveling off into space.

1903 Antoine Henri Becquerel (1852–1908), French physicist, shares the Nobel Prize in physics with the husband-and-wife team of Marie Sklodowska Curie (1867–1934), Polish-French chemist, and Pierre Curie (1859–1906), French chemist. Becquerel wins for his discovery of natural or spontaneous radioactivity, and the Curies win for their later research on this new phenomenon.

1903 Archibald Edward Garrod provides evidence that errors in genes cause several hereditary disorders in human beings. His book *The Inborn Errors of Metabolism* (1909) is the first treatise in biochemical genetics.

1903 Ernest Rutherford (1871–1937), British physicist, and Frederick Soddy (1877–1956), English chemist, explain radioactivity by their theory of atomic disintegration. They discover that uranium breaks down and forms a new series of substances as it gives off radiation.

1903 Walter S. Sutton publishes a paper in which he presents the chromosome theory of inheritance. The theory, which states that the hereditary factors are located in the chromosomes, is independently proposed by Theodor Boveri and is generally referred to as the Sutton–Boveri hypothesis.

1903 William Ramsay (1852–1916), Scottish chemist, and Frederick Soddy(1877–1956), English chemist, discover that helium is continually produced by naturally radioactive substances.

1904 Ernest Rutherford, age of Earth by radioactvity dating.

1904 Hendrik Antoon Lorentz (1853–1928), Dutch physicist, extends his idea of local time (different time rates in different locations) and arrives at what are called the Lorentz transformations. These are mathematical formulas describing the increase of mass, shortening of length, and dilation of time that are characteristic of a moving body. These eventually form the basis of Einstein's special theory of relativity.

1904 William Ramsay (1852–1916), Scottish chemist, receives the Nobel Prize in Chemistry for the discovery of the inert gaseous elements in air, and for his determination of their place in the periodic system.

1905 Albert Einstein (1879–1955), German-Swiss physicist, uses Planck's theory to develop a quantum theory of light which explains the photoelectric effect. He suggests that light has a dual, wave-particle quality.

1905 Albert Einstein (1879–1955), German-Swiss physicist, publishes special theory of relativity.

1905 Albert Einstein (1879–1955), German-Swiss (later German-born American) physicist, publishes an elegantly brief but seminal paper in which he asserts and proves his most famous formula, $E=mc^2$ (Energy = mass times the square of the speed of light squared) relating mass and energy.

1905 Percival Lowell postulates a ninth planet beyond Neptune.

1905 Walther Hermann Nernst (1864–1941), German physical chemist, announces his discovery of the third law of thermodynamics. He finds that entropy change approaches zero at a temperature of absolute zero, and deduces from this the impossibility of attaining absolute zero.

1907 Albert Einstein, equivalence principle and gravitational red shift.

1907 Georges Urbain (1872–1938), French chemist, discovers the last of the stable rare earth elements, and names it lutetium after the Latin name of Paris.

1907 Pierre Weiss (1865–1940), French physicist, offers his theory explaining the phenomenon of ferromagnetism. He states that iron and other ferromagnetic materials form small *domains* of a certain polarity pointing in various directions. When some external magnetic field forces them to be aligned, they become a single, strong magnetic force. This explanation is still accurate.

1908 Tunguska event occurs when a comet or asteroid enters the atmosphere, causing major damage to a forested region in Siberia.

1908 Alfred Wegener proposes the theory of continental drift.

1908 Ernest Rutherford (1871–1937), English physicist, is awarded the Nobel Prize in Chemistry for his investigations into disintegration of the elements and the chemistry of radioactive substances.

1908 Ernest Rutherford (1871–1937), British physicist, and Hans Wilhelm Geiger (1882–1945), German physicist, develop an electrical alpha-particle counter. Over the next few years, Geiger continues to improve this device which becomes known as the Geiger counter.

1908 Percy Williams Bridgman (1882–1961), American physicist, begins a lifetime of pioneering work in the field of high pressures. Working eventually in the unexplored field of attaining 400,000 atmospheres, he is forced to invent much of his equipment himself. As he extends the range of pressures, he becomes the founder of the laws of high pressure physics.

1909 Thomas Hunt Morgan selects the fruit fly *Drosophila* as a model system for the study of genetics. Morgan and his coworkers confirm the chromosome theory of heredity and realize the significance of the fact that certain genes tend to be transmitted together. Morgan postulates the mechanism of “crossing over.” His associate, Alfred Henry Sturtevant demonstrates the relationship between crossing over and the rearrangement of genes in 1913.

1911 Arthur Holmes publishes the first geological time scale with dates based on radioactive measurements.

1911 Ernest Rutherford (1871–1937), British physicist, discovers that atoms are made up of a positive nucleus surrounded by electrons. This modern concept of the atom replaces the notion of featureless, indivisible spheres that dominated atomistic thinking for 23 centuries—since Democritus (c. 470–c.380).

1911 Victor Hess identifies high altitude radiation from space.

1912 Friedrich Karl Rudolf Bergius (1884–1949), German chemist, discovers how to treat coal and oil with hydrogen to produce gasoline.

1913 Charles Fabry (1867–1945), French physicist, first demonstrates the presence of ozone in the upper atmosphere. It is found later that ozone functions as a screen, preventing much of the Sun’s ultraviolet radiation from reaching Earth’s surface. Seventy-five years after the discovery of ozone, in 1985, a hole in the ozone layer over Antarctica is discovered via satellite.

1913 Niels Henrik David Bohr (1885–1962), Danish physicist, proposes the first dynamic model of the atom. It is seen as a very dense nucleus surrounded by electrons rotating in orbitals (defined energy levels).

1913 Between 1911-13, Danish astronomer Ejnar Hertzsprung (1873-1967) and American astronomer Henry Norris Russell (1877-1957) independently develop what is now known as the Hertzsprung-Russell diagram describing stellar evolution.

1913 Using the x-ray spectroscope which they invented, William Lawrence Bragg (1890–1971), Australian-English physicist, and his father William Henry Bragg (1862–1942), make the first determinations of the structures of simple crystals and demonstrate the tetrahedral distribution of carbon atoms in diamonds. Their perfection of x-ray crystallography leads to the later examination of the molecule structure of thousands of crystalline substances.

1914 Ejnar Hertzsprung measures the distance of the Large Magellanic Cloud using Cepheid variable stars.

1914 Ernest Rutherford (1871–1937), British physicist, discovers a positively charged particle he calls a proton.

1915 Albert Einstein (1879–1955), German-Swiss physicist, completes four years of work on his theory of gravitation, or what becomes known as the general theory of relativity.

1915 Richard Martin Willstätter (1872–1942), German chemist, is awarded the Nobel Prize in Chemistry for his research on plant pigments, especially chlorophyll.

1916 Karl Schwarzschild theorizes the existence of black holes.

1917 Albert Einstein, introduction cosmological constant and steady state model of the universe.

1917 Vesto Melvin Slipher observes that most galaxies have red shifts.

1917 Willem de Sitter describes a model of a static universe with no matter.

1918 Harlow Shapley determines the size and shape of our galaxy.

1918 Harlow Shapley measures distance to globular clusters using Cepheid variable stars.

1919 Arthur Eddington records data on the Sun's gravitational deflection of starlight during a solar eclipse, confirming Einstein's general theory of relativity.

1920 Ernest Rutherford (1871–1937), English physicist, names the positively charged part of the atom's nucleus a "proton."

1920 Shapley and Curtis, The Great Debate over the scale and structure of the universe.

1922 Alexsandr Friedmann develops a model of an expanding/oscillating universe with matter included.

1923 Arthur Holly Compton (1892–1962), American physicist, discovers what is later called the Compton effect. While accurately measuring the wavelengths of scattered x rays, he discovers that some of the rays had lengthened their wavelength in scattering. He accounts for this by stating that a *photon* of light strikes an electron, which recoils and subtracts some energy from the photon, thereby increasing its length. It is Compton who coins the term photon to describe light as a particle.

1923 Louis Victor Pierre Raymond de Broglie (1892–1987), French physicist, introduces the particle-wave hypothesis, stating that an electron or any other subatomic particle can behave either as a particle or as a wave. This idea is confirmed in 1927.

1924 Edwin Hubble measures the distance of other galaxies using Cepheid variables in galaxies outside ours.

1925 Robert Andrews Millikan (1868–1953), American physicist, names the radiation coming from outer space *cosmic rays*.

1925 Werner Karl Heisenberg (1901–1976), German physicist, develops a new system of mathematics called matrix mechanics which employs columns of numbers that describe all possible transitions within an atom. The solutions to the matrix correspond to the wavelengths of the hydrogen spectral lines.

1925 Wolfgang Pauli (1900–1958), Austrian physicist, announces his discovery of the exclusion principle which develops into one of the most powerful basic descriptive tools in physics. It states that two electrons with the same quantum numbers cannot occupy the same atom. This principle serves to explain the chemical properties of the elements.

1925 Vesto Slipher argues that red-shifts of light can be interpreted in terms of distance and velocity.

1925 Walter Elsasser, explanation of electron diffraction as wave property of matter.

1926 American Robert Goddard launches the first liquid-fueled rocket capable of stable flight.

1926 Astronomers assert that the Pauli exclusion principle offers an explanation of white dwarf stars.

1926 Enrico Fermi (1901–1954), Italian-American physicist, introduces Fermi-Dirac statistical mechanics. This theory explains the behavior of *clouds* of electrons in a substance and also shows that gas particles obey Pauli's exclusion principle.

1926 Erwin Schrödinger (1887–1961), Austrian physicist, publishes a paper in which he mathematically develops wave mechanics and offers what becomes known as the Schrödinger wave equation. This replaces the electron in the Bohr model of the atom with wave trains. This explanation becomes so satisfactory that it finally places Planck's quantum theory on a firm mathematical basis.

1926 Eugene Paul Wigner (1902–1995), Hungarian-American physicist, develops the principles involved in applying group theory to quantum mechanics and evolves the concept of the symmetry in space and time that marks the behavior of subatomic particles.

1926 Gilbert Newton Lewis (1875–1946), American chemist, first introduces the term *photon* to describe the minute, discrete energy packet of electromagnetic radiation that is essential to quantum theory.

1926 John Desmond Bernal (1901–1971), English physicist, advances x-ray crystallography by developing the Bernal chart with which he can deduce crystal structure by analyzing photographs of x-ray diffraction patterns.

1926 Max Born (1882–1970), German-British physicist, publishes his first paper on the probability interpretation of quantum mechanics. In working out the mathematical basis of quantum mechanics, he gives electron waves a probabilistic interpretation as to their behavior.

1927 Astronomer Jan Oort argues that observations indicate the solar system orbits a galactic center and that the Milky way is a spiral shaped galaxy.

1927 Big bang theory is formulated to provide a coherent cosmology consistent with new developments in quantum and relativity physics.

1927 Charles Lindbergh makes first solo transatlantic flight.

1927 Georges Lemaitre offers a model of an expanding universe.

1927 Hermann Joseph Muller induces artificial mutations in fruit flies by exposing them to x rays. His work proves that mutations result from some type of physical-chemical change. Muller wrote extensively about the danger of excessive x rays and the burden of deleterious mutations in human populations.

1927 Niels Henrik David Bohr (1885–1962), Danish physicist, states complementarity principle, that a phenomenon can be considered in each of two mutually exclusive ways, and each way is valid in its own terms. He applies it specifically to the simultaneous wave and particle behavior of an electron, but it later is used by disciplines besides atomic physics.

1927 Paul Adrien Maurice Dirac (1902–1984), English physicist, develops equations that unite quantum mechanics and relativity theory.

1927 Werner Karl Heisenberg (1901–1976), German physicist, postulates his uncertainty principle, also known as the principle of indeterminacy. This states that it is impossible to determine accurately and simultaneously two variables of an electron, such as position and momentum. More generally, it states that when working with atom-sized or subatomic particles, the very act of measuring such particles significantly affects the results obtained. Philosophically, this is a troubling notion, for it calls into question much of traditional beliefs in straightforward cause and effect.

1928 George Gamow (1904–1968), Russian-American physicist, develops the quantum theory of radioactivity which is the first theory to successfully explain the behavior of radioactive elements, some of which decay in seconds and others after thousands of years.

1929 Astronomer Edwin Hubble argues evidence that galaxies are moving away from each other and that the universe is expanding.

1929 Walther Wilhelm Georg Franz Bothe (1891–1957), German physicist, invents *coincidence counting* by using two Geiger counters to detect the vertical direction of cosmic rays. This allows the measurement of extremely short time intervals, and he uses this technique to demonstrate that the laws of conservation and momentum are also valid for subatomic particles.

1929 William Francis Giauque (1895–1982), American chemist, discovers that oxygen is a mixture of three isotopes. This leads to a debate between chemists and physicists concerning an atomic weight standard, which is not resolved until 1961.

1930 Clyde Tombaugh (1906–1997) discovers Pluto.

1931 Paul Adrien Maurice Dirac (1902–1984), English physicist, proposes the antielectron, or positron, a positively charged electron.

1932 James Chadwick (1891–1974), English physicist, proves the existence of the neutral particle of the atom's nucleus, called the neutron. It proves to be by far the most useful particle for initiating nuclear reactions.

1932 John Douglas Cockcroft (1897–1967), English physicist, and Irish physicist Ernest Thomas Sinton Walton (1903–1995), use their new particle accelerator to bombard lithium and produce two alpha particles (having combined lithium and hydrogen to produce helium).This is the first nuclear reaction that has been brought about through the use of artificially accelerated particles and without the use of any form of natural radioactivity. This ultimately proves highly significant to the creation of an atomic bomb.

1932 Karl Jansky makes first attempts at radio astronomy.

1932 Lev Davidovich Landau proposes the existence of neutron stars.

1932 Ruska builds first electron microscope.

1932 Thomas H. Morgan receives the Nobel Prize in Medicine or Physiology for his development of the theory of the gene. He is the first geneticist to receive a Nobel Prize.

1932 Werner Karl Heisenberg (1901–1976), German physicist, wins the Nobel Prize in physics for the creation of quantum mechanics, whose application has led to the discovery of the allotropic forms of hydrogen.

1933 Baade and Zwicky argue that a collapse of a white dwarf may set off a supernova and then produce a neutron star.

1933 Enrico Fermi (1901–1954), Italian-American physicist, develops a theory of beta decay which uses Pauli's *neutrino* as part of its explanation.

1934 Arnold O. Beckman (1900–), American chemist and inventor, invents the pH meter, which uses electricity to accurately measure a solution's acidity or alkalinity.

1934 Enrico Fermi (1901–1954), Italian-American physicist, bombards uranium with neutrons and obtains not only a new element, number 93 (neptunium), but also a number of other products that he is unable to identify. What he eventually discovers is that he has not only created the first synthetic element, but he has also produced the first nuclear fission reaction.

1934 Frédéric Joliot-Curie (1900–1958) and Irène Joliot-Curie (1897–1956), husband-and-wife team of French physicists, discover what they call *artificial radioactivity*. They bombard aluminum to produce a radioactive form of phosphorus. They soon learn that radioactivity is not confined only to heavy elements like uranium, but that any element can become radioactive if the proper isotope is prepared. For producing the first artificial radioactive element they win the Nobel Prize in chemistry the next year.

1934 Leo Szilard (1898–1964), Hungarian-American physicist, first conceives of the idea of a nuclear chain reaction (in which a neutron induces an atomic breakdown, which releases two neutrons which break down two more atoms, and so on). Although his method uses beryllium rather than uranium and would be impractical, it is correct in principle. He keeps it a secret, foreseeing its importance in making nuclear bombs, but it is soon discovered by other scientists.

1935 Robert Watson-Watt develops RADAR.

1935 Subrahmanyan Chandrasekhar, calculation of mass limit for stellar collapse of a white dwarf.

1936 Carl David Anderson (1905–1991), American physicist, discovers the *muon*. While studying cosmic radiation, he observes the track of a particle that is more massive than an electron but only a quarter as massive as a proton. He initially calls this new particle, which has a lifetime of only a few millionths of a second, a mesotron, but it later becomes known as a muon to distinguish it from Yukawa's meson.

1936 Theodosius Dobzhansky publishes *Genetics and the Origin of Species*, a text eventually considered a classic in evolutionary genetics.

1937 Emilio Segre (1905–1989), Italian-American physicist, and Carlo Perrier bombard molybdenum with deuterons and neutrons to produce element 43, technetium. This is the first element to be prepared artificially that does not exist in nature.

1938 Bethe, Critchfield, von Weizsacker, argue that stars are powered by the CNO-cycle of nuclear fusion.

1939 Leo Szilard (1898–1964), Hungarian-American physicist, and Canadian-American physicist, Walter Henry Zinn (b. 1906), confirm that fission reactions (nuclear chain reactions) can be self-sustaining using uranium.

1939 Linus Carl Pauling (1901–1994), American chemist, publishes *The Nature of the Chemical Bond*, a classic work that becomes one of the most influential chemical texts of the twentieth century.

1939 Lise Meitner (1878–1968), Austrian-Swedish physicist, and Otto Robert Frisch 1904–1979), Austrian-British physicist, suggest the theory that uranium breaks into smaller atoms when bombarded. Meitner offers the term *fission* for this process.

1939 Niels Hendrik David Bohr (1885–1962), Danish physicist, proposes a liquid-drop model of the atomic nucleus and offers his theory of the mechanism of fission. His prediction that it is the uranium-235 isotope that undergoes fission is proved correct when work on an atomic bomb begins in the United States.

1939 Oppenheimer and Snyder argue that a collapsing neutron star forms what would later be termed a black hole.

1941 Arnold O. Beckman (1900–), American physicist and inventor, invents the spectrophotometer. This instrument measures light at the electron level and can be used for many kinds of chemical analysis.

1941 R. Sherr, Kenneth Thompson Bainbridge, American physicist, and H. H. Anderson produce artificial gold from mercury.

1942 Astronomer Grote Reber constructs radio map of the sky.

1942 Enrico Fermi (1901–1954), Italian-American physicist, heads a Manhattan Project team at the University of Chicago that produces the first controlled chain reaction in an atomic pile of uranium and graphite. With this first self-sustaining chain reaction, the atomic age begins.

1943 First operational nuclear reactor is activated at the Oak Ridge National Laboratory in Oak Ridge, Tennessee.

1943 J. Robert Oppenheimer (1904–1967), American physicist, is placed in charge of United States atomic bomb production at Los Alamos, New Mexico. He supervises the work of 4,500 scientists and oversees the successful design construction and explosion of the bomb.

1944 Otto Hahn (1879–1968), German physical chemist, receives the Nobel Prize in Chemistry for his discovery of nuclear fission.

1944 Sin-Itiro Tomonaga (1906–1979), Japanese physicist, works out the theoretical basis for quantum electrodynamics independently of American physicists Richard Philips Feynman (1918–1988) and Julian Seymour Schwinger (1918–1994) (who also work independently of one another). This method allows the behavior of electrons to be determined with far greater precision than before. It also leads to the formulation of quantum electrodynamics (QED).

1945 First atomic bomb is detonated by the United States near Almagordo, New Mexico. The experimental bomb generates an explosive power equivalent to 15–20 thousand tons of TNT.

1945 Joshua Lederberg and Edward L. Tatum demonstrate genetic recombination in bacteria.

1945 United States destroys the Japanese city of Hiroshima with a nuclear fission bomb based on uranium-235 on August 6. Three days later, a plutonium-based bomb destroys the city of Nagasaki. Japan surrenders on August 14 and World War II ends. This is the first use of nuclear power as a weapon.

1946 George Gamow proposes the Big Bang hypothesis.

1947 A U.S. aircraft travels faster than the speed of sound.

1947 First carbon-14 dating.

1948 Gamow and others assert theory of nucleosynthesis is consistent with hot big bang.

1950 Astronomer Jan Oort offers explanation of origin of comets.

1951 Rosalind Franklin obtains sharp x-ray diffraction photographs of DNA.

1952 Alfred Hershey and Martha Chase publish their landmark paper “Independent Functions of Viral Protein and Nucleic Acid in Growth of Bacteriophage.” The famous “blender experiment” suggests that DNA is the genetic material. When bacteria are infected by a virus, at least 80% of the viral DNA enters the cell and at least 80% of the viral protein remains outside.

1952 First thermo-nuclear device is exploded successfully by the United States at Eniwetok Atoll in the South Pacific. This hydrogen-fusion bomb (H bomb) is the first such bomb to work by nuclear fusion and is considerably more powerful than the atomic bomb exploded over Hiroshima on August 6, 1945.

1952 First use of isotopes in medicine.

1953 James D. Watson and Francis H. C. Crick publish two landmark papers in the journal *Nature*: “Molecular structure of nucleic acids: a structure for deoxyribose nucleic acid” and “Genetical implications of the structure of deoxyribonucleic acid.” Watson and Crick propose a double helical model for DNA and call attention to the genetic implications of their model. Their model is based, in part, on the x ray crystallographic work of Rosalind Franklin and the biochemical work of Erwin Chargaff. Their model explains how the genetic material is transmitted.

1953 Murray Gell-Mann (b. 1929), American physicist, suggests that basic particles contain an intrinsic property known as *strangeness* that can explain a number of new observations being made about them. A similar concept is developed independently by the Japanese physicist Kazuhiko Nishijima (b. 1926).

1953 Stanley Miller produces amino acids from inorganic compounds similar to those in primitive atmosphere with electrical sparks that simulate lightning.

1953 USGS decides to split the Carboniferous into Mississippian and Pennsylvanian.

1954 Linus Carl Pauling (1901–1994), American chemist, receives the Nobel Prize in Chemistry for his research into the nature of the chemical bond and its applications to the elucidation of the structure of complex substances.

1955 First synthetic diamonds are produced in the General Electric Laboratories.

1956 Joe Hin Tijo and Albert Levan prove that the number of chromosomes in a human cell is 46, and not 48, as argued since the early 1920s.

1956 Neutrino discovered at Los Alamos.

1957 Francis Crick proposes that during protein formation each amino acid is carried to the template by an adapter molecule containing nucleotides and that the adapter is the part that actually fits on the RNA template. Later research demonstrates the existence of transfer RNA.

1957 Soviet Union launches Earth’s first artificial satellite, Sputnik, into earth orbit.

1958 Astronomer Martin Ryle argues evidence for evolution of distant cosmological radio sources.

1958 George W. Beadle, Edward L. Tatum, and Joshua Lederberg are awarded the Nobel Prize in Medicine or Physiology. Beadle and Tatum are honored for the work in *Neurospora* that led to the one gene-one enzyme theory. Lederberg is honored for discoveries concerning genetic recombination and the organization of the genetic material of bacteria.

1958 National Aeronautics and Space Administration (NASA) established .

1959 Soviet Space program sends space probe to impact Moon.

1961 Edward Lorenz advances chaos theory and offers possible implications on atmospheric dynamics and weather.

1961 Murray Gell-Mann (b. 1929), American physicist, and Israeli physicist Yuval Ne’Eman (b. 1925), independently introduce a new way to classify heavy subatomic particles. Gell-Mann names it the *eightfold* way, and this system accomplishes for elementary particles what the periodic table did for the elements.

1961 Soviet Union launches first cosmonaut, Yuri Gagarin, into Earth orbit.

1962 James D. Watson, Francis Crick, and Maurice Wilkins are awarded the Nobel Prize in Medicine or Physiology for their work in elucidating the structure of DNA.

1963 Fred Vine and Drummond Matthews offer important proof of plate tectonics by discovering that oceanic crust rock layers show equidistant bands of magnetic orientation centered on the a site of sea floor spreading.

1964 Astronomers discover quasars.

1964	John Bell asserts a quantum inequality that limits the possibilities for local hidden variables in quantum theories.
1964	Roger Penrose defines nature of what would later be termed a black hole as a singularity or a dimensionless point of extreme mass.
1965	Arno Allan Penzias and Robert Woodrow Wilson detect cosmic background radiation.
1966	Marshall Nirenberg and Har Gobind Khorana lead teams that decipher the genetic code. All of the 64 possible triplet combinations of the four bases (the codons) and their associated amino acids are determined and described.
1966	Robert Sanderson Mulliken (1896–1986), American chemist, receives the Nobel Prize in Chemistry for his fundamental work concerning chemical bonds and the electronic structure of molecules by the molecular orbital method.
1966	X-ray source Cygnus X-1 discovered.
1967	Bell and Hewish discover pulsars.
1967	John Wheeler introduces the term "black hole".
1968	Electroweak theory—unification of electromagnetism with the weak force—achieved by American physicist Sheldon Lee Glashow (1932-), Pakistani physicist Abdus Salam (1926-1996), and American physicist Steven Weinberg (1933-).
1968	Joseph Weber, first attempt at a gravitational wave detector.
1969	Apollo 11 mission to the Moon. U.S. astronauts Neil Armstrong and Buzz Aldrin become first humans to walk of another world.
1969	Max Delbrück, Alfred D. Hershey, and Salvador E. Luria were awarded the Nobel Prize in Medicine or Physiology for their discoveries concerning the replication mechanism and the genetic structure of viruses.
1971	Cygnus X-1 identified as black hole candidate.
1972	Discovery of 2 million year old humanlike fossil, *Homo habilis,* in Africa.
1972	Gell-Mann theorizes QCD (Quantum Chromo Dynamics) and unification theory that includes strong force).
1972	Paul Berg and Herbert Boyer produce the first recombinant DNA molecules. Recombinant technology emerges as one of the most powerful techniques of molecular biology. Scientists are able to splice together pieces of DNA to form recombinant genes. As the potential uses, therapeutic and industrial, become increasingly clear, scientists and venture capitalists establish biotechnology companies.
1975	Scientists at an international meeting in Asilomar, California, call for the adoption of guidelines regulating recombinant DNA experimentation.
1976	U.S. Viking spacecraft lands and conducts experiments on Mars.
1977	Robotic submarine "Alvin" explores mid-oceanic ridge and discovers chemosynthetic life.
1977	Voyager spacecraft launched; contains golden record recording of Earth sounds.
1984	Ozone hole over Antarctica discovered.
1988	The Human Genome Organization (HUGO) is established by scientists in order to coordinate international efforts to sequence the human genome. The Human Genome Project officially adopts the goal of determining the entire sequence of DNA comprising the human chromosomes.
1990	Hubble Space Telescope launched.
1991	K-T event impact crater identified near the Yucatan Peninsula.
1991	Andrew A. Griffith, American chemist, uses an atomic force microscope to obtain extraordinarily detailed images of the electrochemical reactions involved in corrosion.
1993	George Washington University researchers clone human embryos and nurture them in a Petri dish for several days. The project provokes protests from ethicists, politicians and critics of genetic engineering.
1994	Astronomers observe comet Shoemaker-Levy 9 (S-L 9) colliding with Jupiter.
1994	Hubble Space Telescope confirms existence of black holes.
1994	Researchers at Fermilab discover the top quark. Scientists believe that this discovery may provide clues about the genesis of matter.
1995	Mayor and Queloz identify first extra-solar planet, a Jupiter-like planet orbiting an ordinary star.
1995	Paul Crutzen (1933–), Dutch meteorologist, Mario Molina (1943–), Mexican American chemist, and R. Sherwood Rowland (1927–), American atmospheric chemist, receive the Nobel Prize in Chemistry for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone.
1997	Microscopic analysis of Murchison meteorite lead some scientists to argue evidence of ancient life on Mars.
1997	Mars Pathfinder vehicle studies and photographs Martian surface.

1998 Ian Wilmut announces the birth of Polly, a transgenic lamb containing human genes.

1998 Two research teams succeed in growing embryonic stem cells.

1999 Scientists announce the complete sequencing of the DNA making up human chromosome 22. The first complete human chromosome sequence is published in December 1999.

2000 Astronomers discover a galaxy that is 18.6 billion light-years away from Earth. This is the most remote object ever observed. Scientists speculate that this galaxy was formed when the universe was one-sixteenth its present age.

2001 In February 2001, the complete draft sequence of the human genome is published. The public sequence data is published in the British journal *Nature* and the sequence obtained by Celera is published in the American journal *Science.*

2002 Satellites capture images of icebergs more than ten times the size of Manhattan Island breaking off Antarctic ice shelf.

GENERAL INDEX

Page numbers in bold type indicate primary treatment of a subject; those in italics indicate graphic material.